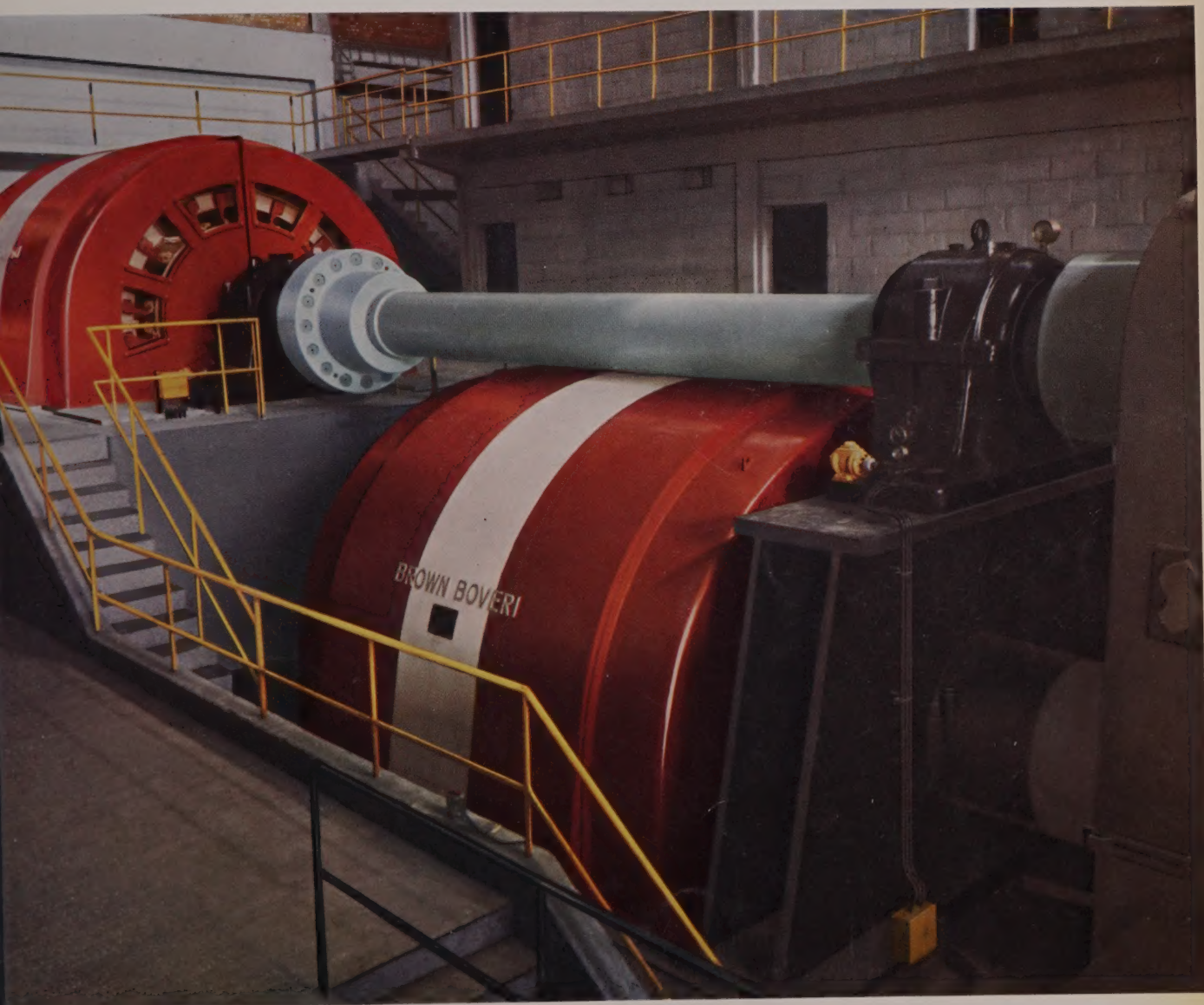
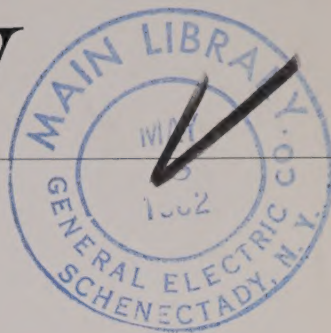
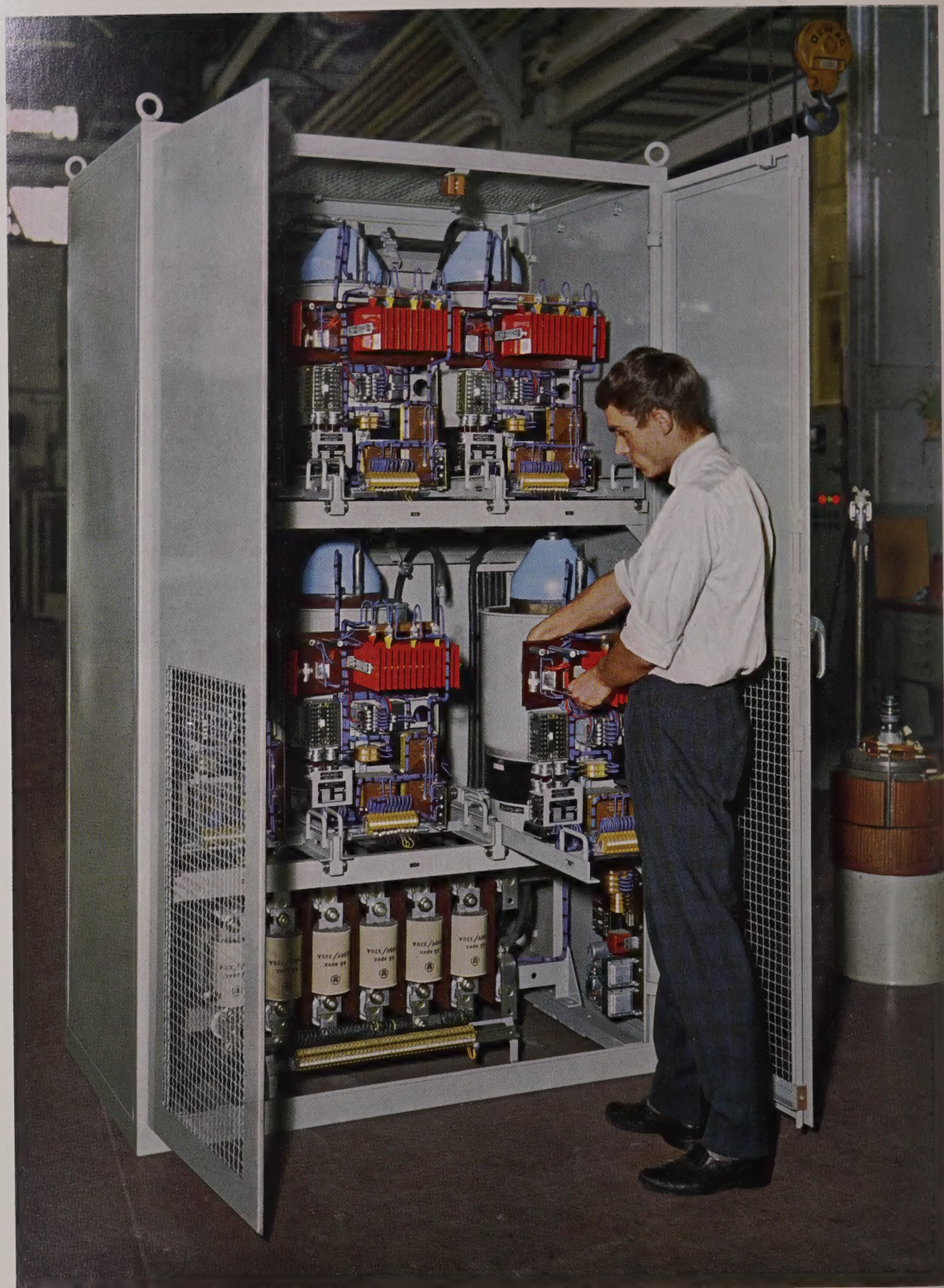


BROWN BOVERI REVIEW

Rolling-Mill Drives



Twin drive of a rolling mill,
comprising two double-armature motors, each rated 4 500 kW, $0 \pm 40 \pm 80$ rev/min, cut-out torque 300 mt



*Cabinet containing six single-anode
mercury-arc converters, combined with their auxiliaries as drawout packaged units*

THE BROWN BOVERI REVIEW

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INTRODUCTION

IN NOVEMBER 1956 a special issue of the Brown Boveri Review was devoted to the electrical equipment of rolling-mill drives. In it the main accent was laid on the increasing tendency to employ the mercury-arc converter to provide the necessary direct current, and the change from open-loop to closed-loop control. Fundamentally there have been no great changes in this technique, but new knowledge has been gained in the meantime and new problems have arisen out of the constant desire of the steelworks to attain higher output with improved quality.

In this present special number on rolling-mill drives the present state of the art in this sphere will be dealt with, at least as far as the major aspects are concerned, and a brief account given of some installations recently taken into service.

The increased employment of mercury-arc converters continues, as expressed by the following statistics: In the last ten years the Company and its associates have supplied the electrical equipment for 42 continuous hot-rolling mills with an aggregate drive power of over a quarter of a million kilowatts, only one of which — installed in 1956 — employed rotating converters to feed the motors. In the same period the drives have been supplied for 38 reversing mills with cut-out torques up to 600 mt, of which 35 are fed by mutators. In the cold-strip mills there is a distinct tendency to lower the lower limit of powers at which mutators can be employed economically. For instance, of the 100 cold-strip mills for which equipment has been provided since 1950, one quarter of this total is already equipped with mercury-arc converters.

Another notable advance is the use of single-anode converters for reversing d.c. drives. These tanks are able to withstand a higher short-time overload than the multi-anode units and can be combined in various circuit arrangements. On account of these advantages a new series of packaged single-anode air-cooled and pumpless tanks has been devised, with ratings of 100 and 300 A, a detailed description of which is given in some of the articles that follow.

The question of repercussions on the supply system caused by mutator-fed heavy industrial drives has been given close consideration, and every effort made to find ways and means of reducing these effects. As a result it has proved possible to use mutators in relatively weak networks. This problem is also dealt with in a comprehensive article.

Control systems have been developed and perfected still further. Based on the principles of, and the excellent experience gained with electronic equipment for the control of rolling mills, a completely new, universally applicable building-block system, known as the Brown Boveri Electronic System, was brought out; a description of this equipment and many aspects of its application appeared in a special issue (No. 10/11, 1960) of the Review. The elements all work with standardized signals and are flexibly adaptable to various possible combinations. The control units in this system are all transistorized printed-circuit modules which, compared with the former designs with electron tubes, benefit from the great reduction in the space occupied. As output units it is possible to use mutators, silicon or mercury-vapour thyratrons, magnetic amplifiers and transistorized power stages. Power stages are available to suit almost all possible operating conditions.

As far as industrial applications are concerned, the Brown Boveri electronic system, in its range 1, possesses a complete programme of building blocks for analogue techniques, augmented by digital elements for use up to a frequency of 1 kc/s. For high-grade digital circuits, such as positional controls, the elements of range 2 with a maximum working frequency of 100 kc/s are available. All elements of these two ranges, whether for analogue or digital operation, are designed on the same lines and can be flexibly combined, both electrically and constructionally. To control all kinds of main and auxiliary rolling-mill drives, exclusive use is made nowadays of the elements of the Brown Boveri electronic system. These not only fulfil the most stringent requirements of modern drive techniques, but at the same time serve as a basis for the automation of rolling mills, as they can be easily adapted for data logging and processing. All aspects of the problems arising out of the automation of rolling mills are receiving close attention, as will be gathered from the opening article in this number. This important subject can produce revolutionary solutions in the sphere of heavy industrial drives.

It is hoped that this special number will provide a comprehensive and descriptive review of some of the varied problems, which could only be briefly mentioned in this introduction.

(KME)

U. MATTA

R. ZWICKY

SOME ASPECTS OF AUTOMATION IN ROLLING MILLS

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The article deals with some of the fundamental aspects of automation in rolling mills. Following a general discussion of the purpose of automation, the author describes four successive stages. The suitability of the various methods of rolling for automation are examined and the necessary preliminary work explained. In conclusion, the present state of Brown Boveri achievements in this sphere is briefly outlined.

AUTOMATION of industrial processes, in its widest sense, implies the complete replacement of those human faculties concerned with physical effort, observation, memorizing and taking decisions, by mechanical, electrical, magnetic or hydraulic devices. Expressed another way, automation is complete when machines are supervised and controlled by machines. While the first industrial revolution greatly increased man's capabilities in the spheres of the production and utilization of energy, the second industrial revolution, as automation has already been named, aims at taking from him the responsibility for guiding and controlling those processes whose complexity and speed of execution tax his reaction to the utmost limit, or which are continually repeated in the same sequence. If we consider, for example, the various rolling processes from this aspect, it will be immediately evident that this opens up enormous prospects for the project engineer.

Purpose of Automation

The first task is to define the aims to be achieved by the introduction of automation. If these aims are enumerated consecutively, the following picture is obtained.

a. Increasing production

This contains the requirement that an existing installation be utilized to the limit of its capacity and

the percentage wastage kept as low as possible. This not only means that the drives must be run at the limit of their load-carrying capacity, but also that time spent in manipulation, or otherwise unproductive, be kept as short as possible.

b. Improving quality

Apart from the price of a product, its quality is a factor which governs its sales success. It must therefore be the task of automation to eliminate as far as possible all those factors which adversely affect the quality of the final product.

c. Reduction of the process costs

This aim is partly achieved by the requirement in a. But in addition the reduction of wear and tear on the mechanical and electrical parts of the installation must also be mentioned. By automation, the movements and switching actions needed for the execution of the process can be reduced to a minimum. The extension of this to the entire installation reduces the risk of stoppages and prolongs the useful life.

d. Relieving the operating staff

Nowadays the operators are completely bound to the working sequence of the machines. Thus, the task of driving a modern, high-output billet mill imposes tremendous demands on the reaction of the operators. This strain can be relieved by automation, although the operator cannot be dispensed with altogether. He has to perform new duties in his capacity as superior authority.

e. Making new processes possible

This aim probably does not apply to rolling techniques at present, but it is quite feasible for methods

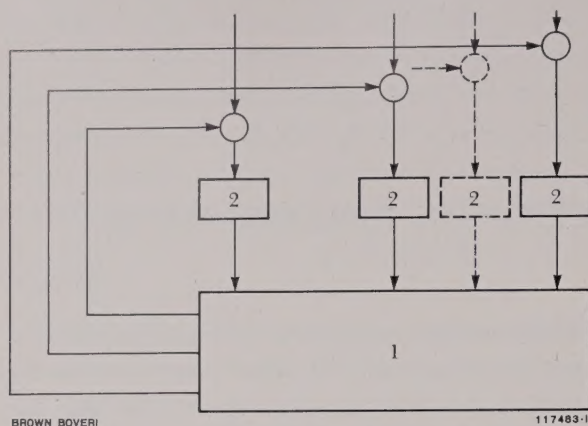


Fig. 1. - Process with several controlled variables

The vertical arrows denote the reference inputs

1 = Process

2 = Control equipment

to be developed in the future, in which the rate of human reaction is exceeded. Such developments are only made possible by automation.

Stages in Automation

Considering the wide field of automation somewhat more closely, it may be seen to comprise four distinct stages:

Close-loop control

Programming

Data logging and reduction

On-line, program-controlled data processing

Closed-loop control

Here the task is to make a particular quantity follow a reference input as accurately as possible, independent of all external and internal disturbance factors. One control loop can only refer to one physical quantity. An automatic control system therefore always contains a number of control loops (Fig. 1).

Programming

This is the task of a device which can lay down a group of reference inputs. The sequence with respect to time in which these instructions are given is determined by the material passing through the machine

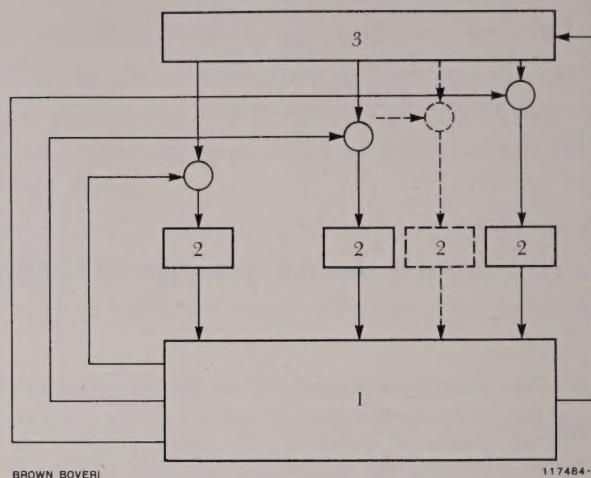


Fig. 2. - Process with several controlled variables and program control

The reference inputs are provided by the programming system. The arrow on the right indicates that the reference input is picked off by the material itself.

1 = Process

2 = Control equipment

3 = Programming system

or process. Programming assumes that the actual procedure was precisely stipulated in advance for all phases of the process (Fig. 2). Consequently program control requires a store for the program, i.e. the group of reference inputs. It must also have elements for encoding and decoding, as well as converters in which the information, frequently provided in digital form, is converted into analogue form. For simple processes with a small number of different programs, combinations of decade switches are most commonly used as stores and programming devices. If, however, a process has to be performed in which the information content, though limited in extent, has to be frequently changed, the most suitable program carrier is the punched card. The program is sampled by a punched card reader and transferred to an instruction register, from which the various reference inputs are then called off by the material being handled. To change the program it is merely necessary to insert another card in the reader. For programs with a very large information content the limited storage capacity of the punched card is no longer adequate. In this case it is preferable to use punched tape.

Data logging

A data logging system is one which can be given various data by hand, and is fed direct with measurements and, if necessary, combines these data and prints them out either in clear or in the form of a punched card. Hence the data logging system has to contain analogue-to-digital converters, encoding devices, addressing devices, stores, arithmetic unit and a means of reading out, according to the requirements. The encoding devices transform the digital signals from the analogue-to-digital converter into code form suitable for further processing. The addressing device allows storage space to be allocated for definite incoming information. The stores are provided in the form of static or core stores, according to the required capacity. The computer has to perform the algebraic operations, i.e. addition, subtraction, multiplication and division. The read-out device reads out the results in the correct lines and columns and controls the card punch or the printer for the clear text (Fig. 3).

In a rolling mill the data logging system has two tasks, one of which includes production and quality control. For this task the data have to be emitted in such a form that they can be utilized as they are within the scope of the general scheme of factory management. The other task is obtaining data to determine the relationship between the process variables, such as temperature, resistance to deformation, deformation torque, and so on. Normally a single data logging system is able to perform both tasks. But its structure must be flexible and adaptable. Above all, the second task can be a great help in improving the process as a whole, if the results of the data collection are systematically evaluated. This enables causes of constantly recurring flaws to be recognized and eliminated. Moreover, it enables further insight to be gained into the relationship which must be known if an electronic computer is to be employed later to control the process.

Data processing

The program-controlled on-line data processing installation is a digital electronic computer which automatically calculates the reference inputs for the process out of the information fed in by the data log-

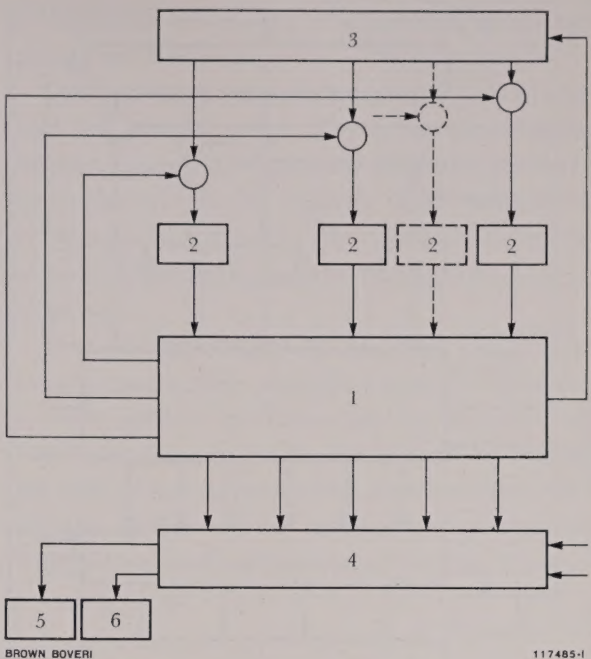


Fig. 3. - Process with several controlled variables, program control and data logging equipment

In this installation the desired quantities are printed out either in clear or in the form of a punched card. The arrows on the right of 4 indicate information introduced by hand.

- 1 = Process
- 2 = Control equipment
- 3 = Programming system
- 4 = Data logging system
- 5 = Card punch
- 6 = Printer

ging system, according to a prescribed program (Fig. 4). To be able to utilize such a machine, the process must be available in the form of a mathematical model. This model can be obtained theoretically or empirically. It should, however, describe the relationship in the process completely and unambiguously. Present knowledge of the rolling process is so far inadequate to permit the establishment of a model of this nature, so that a great deal of spadework is required in this respect. But as soon as the establishment of the fundamentals is achieved, on-line data processing will offer several advantages over program control.

The advantages from the aspects of management and production are particularly obvious when a large number of rolling programs are constantly required and frequent change of program must be

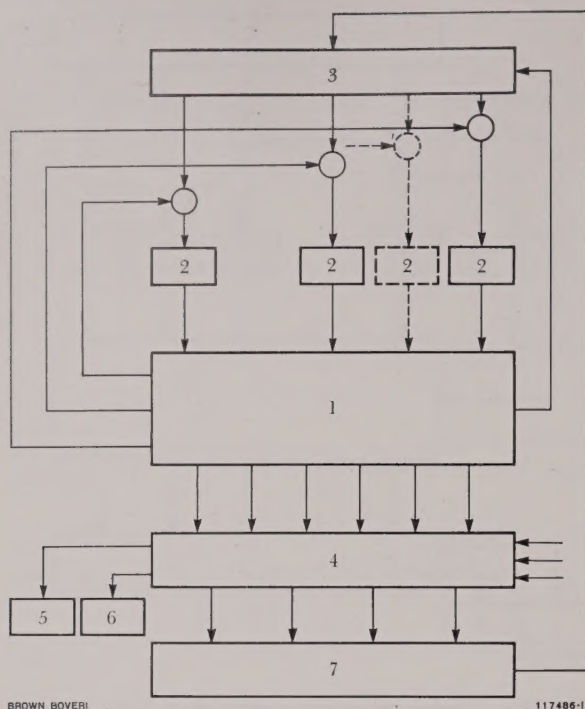


Fig. 4. — Process with several controlled variables, program control, data logging and on-line data processing

The data processing system obtains its information regarding the process from the data logging system and processes it according to a present program. The arrow on the right indicates the transfer of the computed values to the programming system.

- 1 = Process
- 2 = Control equipment
- 3 = Programming system
- 4 = Data logging system
- 5 = Card puncher
- 6 = Printer
- 7 = On-line data processing system

reckoned with. A recent article in the literature [1], for instance, describes the programs used for a slabbing mill, for which 100 000 punched cards were prepared. In such a case the superiority of on-line data processing from the point of view of management is obvious. The other major advantage is that the computer can really utilize the installation to the limit of its capacity. On the other hand, straightforward program control must always be based on certain idealized assumptions regarding dimensions, temperature, weight, etc. But since the actual conditions always differ from the assumed conditions to a certain extent, it is practically impossible to achieve optimum loading of the installation.

If the data logging system and the data processing equipment are treated as a single system, the following functions can be performed:

Information gained from the process.

Solution of the equations giving the relations between the variables, taking into account the conditions for optimizing and provision of the reference inputs for the control loops.

Recognition and localization of abnormal or dangerous situations.

Alarming the control staff when situations arise which are not included in the program of the computer.

Determining and expressing various data which are important as regards economic operation, or for subsequent treatment.

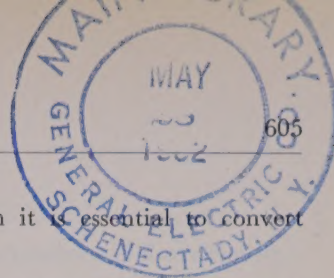
Classification of the product according to quality and quantity.

Preparation of a production report, hourly or per shift.

Whether all these functions can be performed or not will depend on the speed of computation and the time available. Since the computer is directly connected to the process, the time available is governed by the process itself. The computation speed of an electronic digital computer is indeed very fast, but the machine can as a rule only perform one operation at a definite instant. Since all steps consequently have to be performed successively, it is only possible to perform a certain number of steps in a given total time. The question of whether all desired functions can be executed can usually only be answered when the fundamental program of the computer has been established.

Aptitude for Automation

The introduction of automation presumes that the process in question, or the installation concerned, is suitable. This means that automation must be technically feasible and economically justified. The aptitude can be generally described by the following criteria.



The process must have a high output capacity and a correspondingly high production value.

The process should be completely mechanized, i.e. the product does not have to be manipulated by hand, and all settings are performed by motors.

The process should be complex, i.e. involving numerous variables affecting quality and output.

The relationships between the variables must be known theoretically or empirically.

It must be possible to measure the variables continuously.

It must be possible to improve the output and quality of the product.

If these criteria are applied successively to the various methods of rolling, i.e. reversing hot rolling, continuous hot-strip rolling, rod and merchant mills, large tandem mills and reversing cold-rolling mills, the following picture is obtained. All of them are notable for their high output and the resultant low unit price of the product, despite the high production value. A mere increase of 1% in the output can amortize quite a high investment in only a few years.

The installations are completely mechanized. The most important settings, such as the roll gap and the lateral displacement, are performed by auxiliary motors. This does not apply to rod merchant mills where the screwdown is by hand. Since the screwdown setting is one of the most important variables in the whole rolling process, the stipulation that there should be no manipulations by hand is not fulfilled. Hence, in their present form, these installations are unsuitable for anything more than partial program control, and are certainly not ripe for on-line data processing.

The output and quality are affected by numerous variables in all processes. In many cases the exact relationships are not yet known. Furthermore, the rolling speeds are often so high that the speed of reaction of the operators is exceeded.

Since precise scientific fundamentals only exist in the form of hypotheses at present, it is customary to employ well-known empirical methods. It has been asserted that rolling is an art and not a science, but

to introduce automation it is essential to convert the art into a science.

The continuous measurement of the process variables will pose a number of very difficult problems. Measuring methods which allow the friction between the stock and rolls, for example, to be determined, or the spread or forward slip, still have to be discovered. This will necessitate considerable development work.

Thus all processes can be improved with respect to output and quality. An improvement in the output is made possible by shortening the times during which the plant is non-productive and by making the most of the capacity of the drive machines. The average quality can be enhanced by eliminating faulty settings and manipulations due to the operators becoming tired.

Preliminaries to Automation

If a process is to be rendered automatic, the task may be divided into two main fields, namely

analysis of the system and
the technical solution.

The analysis of the system has to be carried out step by step, with close collaboration between the rolling-mill management, the electrical engineers and the mechanical engineers supplying the equipment; it will provide the following information.

The fundamental task of automation, i.e. increasing the output, obtaining data for the factory management, etc. If several tasks are involved, their respective priority has to be settled.

Determination of the optimum conditions, e.g. shortest pass time, operation of the drives at maximum efficiency, most favourable mean power factor, and the like.

The mathematical model of the process, i.e. the system of equations relating the variables involved. This model may be established theoretically or empirically. In practice the theory will provide the functional relationship, while those parameters which cannot be exactly determined theoretically will have to be settled empirically. If a model

cannot be established on this basis, it may be possible to find a system representing the decisions and actions of the operators. As knowledge of the process increases, this program can be improved and perfected.

The individual operations in the process, their sequence with respect to time and their mutual relationship have to be settled in all details.

The quantities to be measured have to be stipulated and appropriate measuring methods chosen. The question of the measuring method is indeed one of the most important in the whole problem.

When considering these tasks in the analysis of the system it will be recognized that a whole series of fundamental questions have to be studied. Brown Boveri commenced this study in good time on a general basis. A valuable foundation was provided by the many years' experience in projecting and supplying control systems for rolling-mill drives of all kinds.

As regards the second heading, the technical solution, there is a great deal of preliminary work to be done here too. The tasks expressed in detail by the analysis of the system now have to be solved technically. Since the actual task imposed may vary within wide limits, a building-block system containing all the essential functions is a convenient solution. A system of this kind must include analogue and digital techniques, and permit the free combination of analogue and digital components. All the basic components, such as logic elements, stores, counters, signal delaying elements, the elements for the basic functions, such as addition, subtraction, multiplication and division, the integrating and differentiating elements, amplifiers, function generators, analogue-to-digital and digital-to-analogue converters, etc., must all be available. The building-block system has to be developed on general lines, yet must carefully weigh up all possibilities. The basis thereby created can then be augmented by specially adapted parts to suit individual requirements.

Very severe demands are made on the parts, particularly as regards their reliability. This is a prime consideration for automation. Consequently purely static elements have to be used, which may only be loaded to a fraction of their limiting capacity.

Only carefully selected components of extremely high quality may be employed. When planning the automatic system much can also be done as regards the reliability. Finally it must be borne in mind that the power level has to be sufficiently high to afford a safe margin against stray capacitive and inductive interference.

The above conditions stipulated for the building-block system are all fulfilled by the Brown Boveri electronic system, described in an earlier number of this journal [2, 3]. With this system, which can be extended almost at will, it is possible to solve present problems, as well as those likely to occur in the future.

The Present State of the Art

Bearing in mind the four states of automation, it is easy to recognize that the first stage—closed-loop control—has been introduced almost everywhere in the sphere of rolling-mill drives. Nowadays the speed, current, torque, tension, size of loops, position, etc., are controlled, almost as a general rule. The control systems have reached a high standard, fulfilling all requirements regarding accuracy, rapidity and reliability. Most systems operate on an analogue basis, but for extreme accuracy mixed digital-analogue systems have been employed, the desired values in which are expressed in digital form. However, it must be underlined that almost all closed-loop control systems refer to electrical and mechanical quantities of the drive, e.g. the current and the speed, whereas the actual process variables are not directly controlled as such. This is associated with the difficulty of measuring the desired mechanical quantities economically with the necessary accuracy. Thus, for instance, the tension which the reel of a cold-strip mill has to produce is regulated by keeping the current of the drive motor constant. This current is directly proportional to the tension when the acceleration and loss components are compensated. It would naturally be better to control the tension direct, but this would imply that it must be measurable. There are, of course, dependable tensiometers available, but often they cannot be used, for economic or technological reasons. As measuring techniques progress, there will in future be an increasing tendency to go over

to the direct control of mechanical quantities, which will then be superposed on the control of quantities belonging to the drive.

The second stage—program control—has been adopted already to a certain extent for the screw-down of reversing hot rolling mills and reversing cold-strip mills. Screwdown control is a positioning problem. From the control aspect it requires positional control with a digital input of the desired position, in order to achieve the necessary accuracy of less than 0.1 % of the total travel. The individual gaps are put in in the form of a decadic dimensional number with the aid of a punched tape or decade switches. The actual-value transducers are in the form of servo-systems, whereas the digital desired value is converted into the analogue value via theappings of a transformer. This method has already been described in detail in an earlier article [4]. Here

TABLE I

Operational values of a supposed rolling process in a universal stand with edging stand

Pass No.	n_2/n_1 %	Screw-down mm	Rolling speed as % of max. speed	Entry speed as % of max. speed
1	+ 4	148	70	25
2	— 20	111	70	40
3	+ 4	83.3	85	25
4	— 20	62.5	85	40
5	+ 2	50	100	30

TABLE II

Precoded values for the rolling process in Table I

Pass No.	n_2/n_1 %	Screw-down mm	Rolling speed %	Entry speed %
1	7	1480	2	5
2	8	1110	2	8
3	7	0833	3	5
4	8	0625	3	8
5	6	0500	4	6

TABLE III

Rolling program as represented on the punched card in Fig. 5, using the decimal code (1 from 10)

Address		Information
Column	Line	
1	11	Check on zeroing of punched card
		1st pass
2	1, 2	Screwdown
3, 4 and 5	1–10	
2	3–10	Speed ratio, stand I to stand II
6	1–5	Rolling speed
6	6–10	Entry speed
7–11	1–10	2nd pass
12–16	1–10	3rd pass
		⋮
52–56	1–10	11th pass
of last pass	12	Instruction: slide return
57–72	1–12	Data logging
73–80	11, 12	Instruction word
73–80	1–10	Address of punched card (program number)

it is merely mentioned that resolution to four places of decimals is quite feasible.

Program control of reversing hot mills has, however, already made some progress. For the universal stand and the edging stand of a medium-section mill the Company has supplied a complete program control for the main drive. The program is introduced by decade switches and covers the entry speed, roll speed, and the ratio between the speed n_1 of the universal stand to the speed n_2 of the edging stand. The sequence of the individual instructions is controlled automatically by the rolling stock actuating photocells and pressure cells. This also applies to the automatic initiation of braking and reversing. Preselection of the program by decade switches can be replaced at any time by punched card programming [5]. Table I shows a possible rolling program. This program is first encoded in such a manner that long words, such as ‘minus 20 %’, are replaced by simpler numbers. The result is Table II.

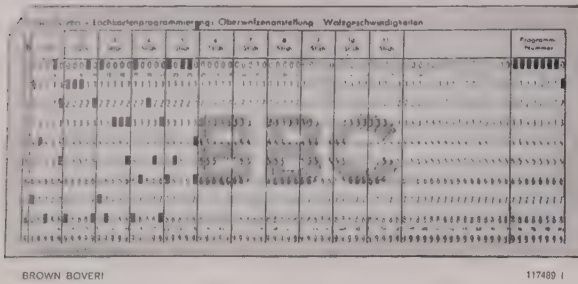


Fig. 5. – Card punched with the program in Tables I, II and III

The transformed program as in Table II is then punched in the card using the decimal code (1 from 10). The address code is shown in Table III, the punched card itself being illustrated in Fig. 5.

The card is produced on a punch (Fig. 6). A stack of uncut cards is inserted in the machine and fed on to the bed by the feed mechanism. The desired address is set up on the keyboard and can then be punched in one or more cards, depending on the number of duplicates required.

At present the Company are working on two reversing hot mills with complete punched-card program control [6]. Apart from the speed variation during a pass, the program also contains the setting of the roll gap, the pusher opening, the tilting process and instructions for the roller tables. The moment at which braking is started is automatically computed in terms of the speed. The instructions for reversing and the settings for the next pass are picked off by the material itself. It should also be noted that the

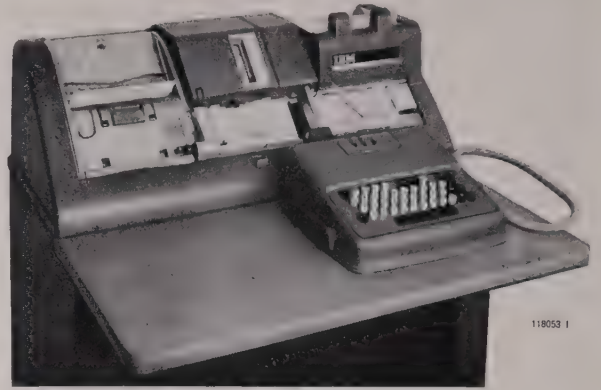


Fig. 6. – Card puncher

movement of the side-guards for tilting is also computed automatically from the diagonals of the ingot. A diagram showing the layout of the program-controlled reversing mill is reproduced in Fig. 7. The flow of information for the automatic billet mill is shown in Fig. 8. The heart of the installation is the instruction register; it stores the number of the roll groove, the roll gap and the rolling speed for each pass. The values of these quantities are transferred via the decoder to the instruction register either by the program preselector or the punched-card reader. From the register the various items of information are conveyed to the units producing the desired values for the positions of the pushers and screwdown, as well as for the speed of the main drive which, in this case, was assumed to be a twin drive with separate desired-value units. The speed program is first

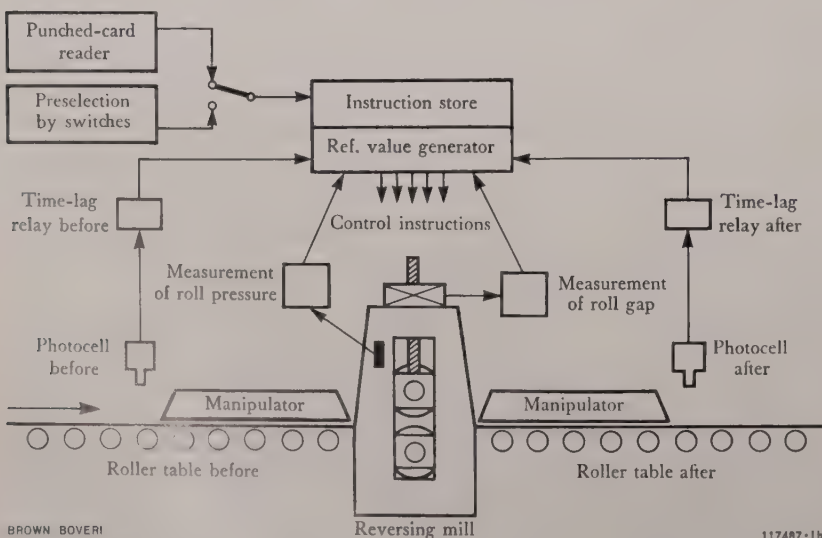


Fig. 7. – Layout of an automatically controlled reversing mill

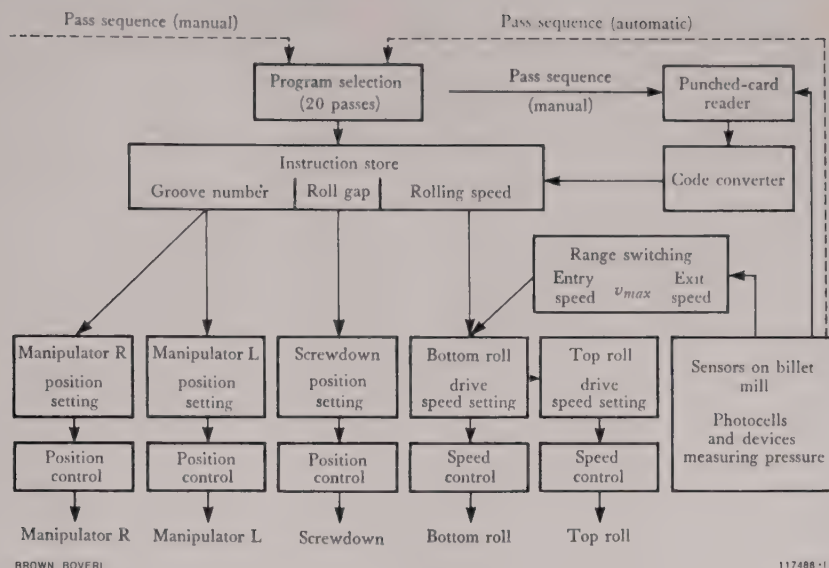


Fig. 8. — Flow of information for an automatically controlled billet mill

prepared in the instruction register, then, by means of sensors on the rolling mill, is switched by a range selector switch from the entry speed to maximum and back to the delivery speed. With automatic control the change to the next pass is effected without any further instructions, as part of the program. If desired, though, it can be effected by hand, even if the preselection of the program is performed by decade switches or punched cards. This is then known as semi-automatic operation. Generally speaking reversing mills will in future always be equipped with some form of program control.

For the third step, data logging, important preliminary work and fundamental studies have already been carried out regarding the design and principle. In the near future such equipment will be introduced to an increasing extent for output and quality control. It represents an essential preliminary stage before on-line data processing. The latter will be introduced in easy stages. Individual functions will be successively extracted from program control and transferred to an electronic computer. The extent to which this is possible will grow as the knowledge of the basic relationships in the rolling process increases. One step, for instance, will be to calculate the speed pro-

gramme during each pass automatically, with due allowance for optimization. It will be years before the last stage is completely introduced, because not only have the mathematical formulae to be established, but also the methods of measurement and suitable transducers still have to be developed, to supply the necessary information to the on-line data processing system.

(KME)

H. MEYER

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REPERCUSSIONS ON THE THREE-PHASE SUPPLY SYSTEM OF CONVERTER-FED D.C. DRIVES

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D.C. drives fed from static converters impose a certain reactive load on the supply system, depending on the method of operation employed. The consumption of reactive power is caused by the combined operation of the transformer and the converter, and depends mainly on the degree of control of the latter. Determination of the reactive load which may be expected and judging what effect this will have on the supply system is a very important task for the project engineers. Apart from circuits with an inherently high power factor, an ideal method of compensating for rapidly rising and frequently repeated reactive load peaks is the synchronous capacitor excited by static converters.

ROLLING-MILL drives fed from static converters consume varying amounts of reactive power from the mains, depending on the working sequence and the particular type of rolling mill. It is important to know whether the d.c. voltage is varied between zero and maximum, how heavy the current is during the time in question, and how rapidly it has to rise. Generally speaking, the variation with respect to time of the direct current and voltage is a primary factor in determining the relationship of active to reactive load for converter-fed drives. Since the armature voltage and current of a d.c. motor are largely governed by the stipulated speed and torque, this determines the relationship between the rolling mill and its electric drive.

Briefly, the following are the various kinds of rolling mills driven by d.c. motors, with the characteristic operating features: Reversing mills producing blooms and slabs, which are characterized by very high torque and very short working sequence, with speeds constantly varying between zero and the maximum in either direction; following these, with progressive deformation of the material, come the cold-strip mills. They convert the strip from the

reversing mill to sheets in a continuous succession of rolling stands. In operation, the rolls of these stands only rotate in the one direction, their speeds only being changed from one programme to the next. The change in speed is mostly effected by varying the excitation current, so that the armature voltage remains almost constantly at its maximum value. At the end of the rolling process are the various types of cold-strip mills and cold tandem mills, where usually the very long strip is wound off and on coilers before and after the rolling stand. If the products from the blooming mill are followed in the same manner, the reversing mills are followed by medium and small reversing stands which turn out billets and sections. The billets are the material from which wire and rod are produced, usually in a succession of several continuous hot mills.

Table I lists the characteristic data of the drives of the mills referred to above. These figures may be regarded as extreme values, which are most interesting when considering the reactive power required from the supply system.

The speed of a d.c. motor is varied from zero to its basic speed by varying the armature voltage. If the motor is fed from static converters, the d.c. voltage has to be varied between wide limits by grid control, resulting in a correspondingly high reactive power consumption from the supply mains.

This reactive load will now be examined, without going into the properties of the grid-controlled mutator. If a d.c. motor, whose field is constantly excited, is uniformly accelerated from zero to the basic speed, the current in the armature circuit is constant throughout the entire run-up period. The magnitude of this current is governed by the rotating masses, which have to be accelerated within a certain

TABLE I

Type of rolling mill	Installed power kW	Power per drive kW	Speed range rev/min	Nature of duty	Duration of sequence s
Reversing blooming and slabbing mill	10 000	5 000	0 ±40/80	intermittent	3–7
Broad-strip mill	40 000	4 500	250/500	continuous*	—
Cold-strip mills	2 000 3 000	2 000	0 ±300/600	intermittent	10–600
Rolling stand		1 500	0 ±500/1800	intermittent	10–600
Coilers					
Reversing mills producing sections and billet	3 000	3 000	0 ±80/160	intermittent	10–60
Continuous billet mills	10 000	1 000	500/1000	continuous*	—
Continuous rod and wire mills	7 500	400–800	500/1200	continuous*	—

* Continuous operation with periods at no-load

period (acceleration torque); another component of the current is determined by the load torque, i.e. the rolling torque. The active power imparted during this period by the motor to the shaft is zero when at standstill, increasing with the speed. Disregarding the losses, the same applies to the active power supplied by the mains.

If the armature circuit is connected to the mains through mercury-arc converters, this means that a current of a certain absolute value has to be supplied by the system during the run-up period. At the beginning of the run-up, i.e. when the speed and active power are zero, this current on the system side can only be reactive. The phase angle between the mains current and voltage only begins to change when the active power rises with increasing speed. The reactive component drops with growing active component. With large reversing drives the starting currents of the d.c. motors are of the order of several thousand amperes, the period between zero and full speed being seldom longer than 1 second. The starting or reversing operations are regularly repeated at intervals of a few seconds. In order to attain such short run-up times, the armature current must rise as rapidly as possible. In most cases, therefore, the maximum possible rate of rise of the armature current is exploited; for large d.c. machines, having

due regard to their commutation properties, this is of the order of three times their rated current per 0.1 s.

Before examining the effects of reactive load surges on the mains any further, it is worth while mentioning the main properties of grid-controlled converters, which have been described as “statically operating multi-pole switching devices”.

Mean D.C. Voltage and Reactive Power of Grid-Controlled Mercury-Arc Converters

For feeding the armature circuit of d.c. machines through converters, at least from medium to high powers, the accepted practice is to employ polyphase converter circuits. From the three voltage vectors of the three-phase supply system it is possible to form polyphase systems by transformation. The individual phases of the anode voltage are successively connected to the cathode through the mercury arc, which always burns at the anode whose phase voltage is positive relative to the voltages of the other phases. In the uncontrolled converter the changeover from one anode to the next always occurs at the natural firing point and the rectified voltage is formed by the upper portions of a sine wave. In the controlled

inverter, on the other hand, this firing point is displaced. Depending on the part of the sine curve connected to the cathode during the arcing time, the mean value of the d.c. voltage may be smaller or larger.

The various anodes carry the current successively and the direct current, which flows between the cathode and the neutral of the transformer, is composed of successive packets of current. In consequence the currents flowing in the various windings of the converter transformer and finally in the supply system have a rectangular or stepped wave-form, thus deviating from the sinusoidal form. Depending on the number of phases and the arrangement of the circuit, the current in the three-phase system is distorted and harmonics are produced. If the d.c. voltage is varied by grid control, the current in the mains is displaced relative to the voltage; reactive power is consumed.

Speaking in general terms of the effect of converter-fed drives on the a.c. mains, it is usually the effect of the harmonics imposed on the three-phase current which is meant, together with the reactive load, which varies in magnitude according to the nature of the drive and the extent of grid control. These factors attain their maximum with reversing drives of blooming mills, where the load may rise to three times the effective d.c. load. These inductive load surges, which—particularly with reversing drives of blooming mills—are repeated at intervals of 2 to 5 s, make it very difficult to maintain the mains voltage, even when the system forms part of a network supplying an area with a very high load density. To correctly

judge these requirements on the supply system and to estimate the effect, it is necessary to know something about the combination of converter and transformer. The general electrical conditions in the converter will therefore first be recalled by referring to the simple hexapulse mid-point connection. This connection has hardly any practical significance, but it does allow the phenomena to be clearly illustrated. First the curve of the d.c. voltage may be studied, consisting of a p -pulse symmetrical system provided by the converter. It is assumed that the individual phase voltages are equal, with the r.m.s. value U_{v0} , as given by

$$U_{v0} = \frac{U_{vm}}{\sqrt{2}} \quad (1)$$

where

U_{v0} = the r.m.s. value of the fundamental wave

U_{vm} = the peak value of the anode voltage.

Fig. 1 shows the fundamental with its r.m.s. value and the curve of the ideal d.c. voltage for pulse numbers of $p = 3$ or 6. As will be observed, the arcing time for each anode is $2\pi/p$. The mean value of the ideal d.c. voltage U_{d0} is shown as a multiple of the r.m.s. value of the fundamental for the pulse numbers 3 and 6.

The formation of the d.c. voltage from the upper parts of the sinusoidal voltage results in harmonics in the d.c. For reasons of periodicity, the only harmonics that can appear are those given by a whole-number multiple of the pulse number p . Associated with each harmonic of the d.c. voltage are two a.c. harmonics having the adjacent ordinal numbers. The

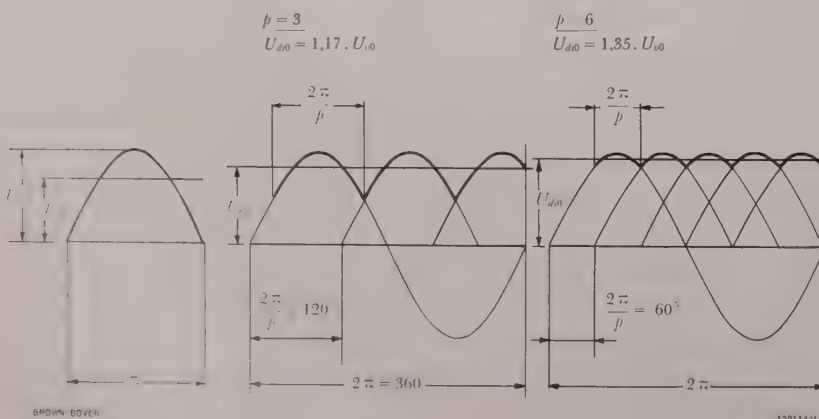


Fig. 1. — Curve of the ideal d.c. voltage for pulse numbers of 3 and 6

U_{vm} = Peak value of the anode voltage

U_{v0} = R.M.S. value of the fundamental wave

U_{d0} = Mean ideal d.c. voltage

magnitude of the harmonic current produced in the primary system by the converter is governed solely by the number of phases of the transformer winding on the converter side. The nature and the importance of the repercussions of primary harmonics was dealt with the article on pages 144–51 of the Brown Boveri Review 1955, Vol. 42, No. 4/5. The relationship between the effective harmonics of the d.c. and the primary a.c., and their variation with the degree of control and the impedance voltage of the transformer, is contained in IEC publication No. 84, issued in 1957.

The best way to gain a clear picture of the phenomena involved in the conversion of current is to start with the direct current flowing between the cathode of the converter and the neutral of the transformer, splitting it up between the individual anodes and by determining the primary currents in the transformer from the anode currents obtained. With suitable combinations it is finally possible to obtain the currents taken from the supply system. This step-by-step procedure is shown in Fig. 2 for a simple hexapulse mid-point circuit, for which the primary winding is in delta. From this illustration the reason for the stepped wave-form of the current on the a.c. side is evident. During the arcing time of anode 3 the cathode is connected to the secondary winding *U* of the converter transformer. Flowing in the circuit from the cathode, through the load, back to the neutral of the transformer, is the current *I_d*. As usual for such basic considerations, this circuit is assumed to possess an infinitely large inductance, thus eliminating all pulsation from the direct current. A corresponding current also flows in the winding *U* on the mains side of the converter transformer, producing mains currents in the phases *R* and *S*, in the same sense in phase *R* and in the opposite sense in phase *S*. If this analysis is carried out for all anodes concerned with carrying current, the mains currents of the converter set are obtained. The individual current blocks and their fundamental wave are indicated in Fig. 3. The shape of the mains current is shown again in Fig. 3, with the fifth and seventh harmonics as well as the fundamental. The ratio of the r.m.s. value of the primary current to the r.m.s. value of its fundamental is referred to as the distortion factor *v* of the uncontrolled converter with purely resistive load.

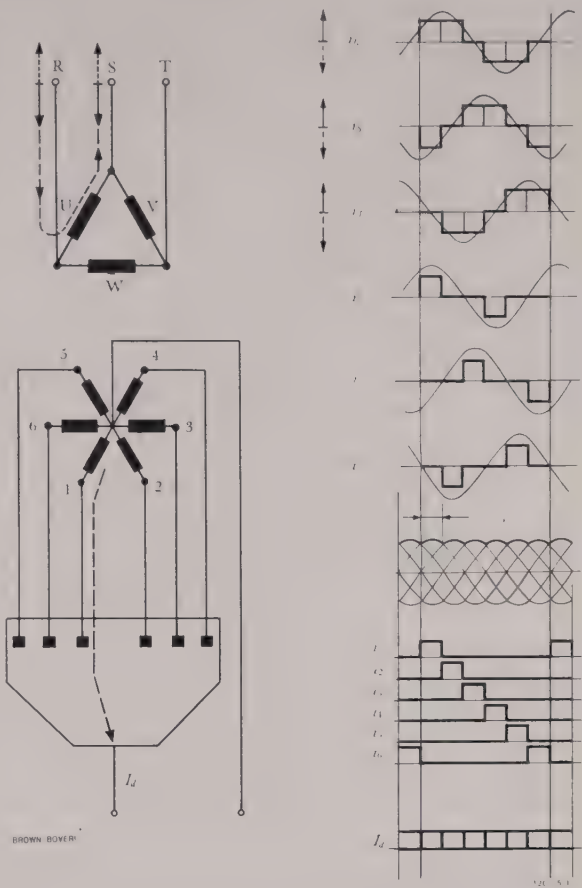


Fig. 2. – Curves of the currents in a hexapulse mercury-arc converter

- i_R, i_S, i_T = Mains currents
- i_U, i_V, i_W = Currents in the line-side winding of the converter transformer
- 1, 2, 3, 4, 5, 6 = Secondary transformer phases
- $i_1, i_2, i_3, i_4, i_5, i_6$ = Anode currents of transformer phases
- I_d = Direct current

This factor indicates the extent of the distortion power caused by the harmonics. Table II shows its values for three, six and twelve-pulse systems. Compared with the reactive component caused by the commutation in the converter and its grid control, and finally by the reactive power of magnetization, this factor is of minor significance.

TABLE II

<i>p</i>	3	6	12
<i>v</i>	0.827	0.955	0.988

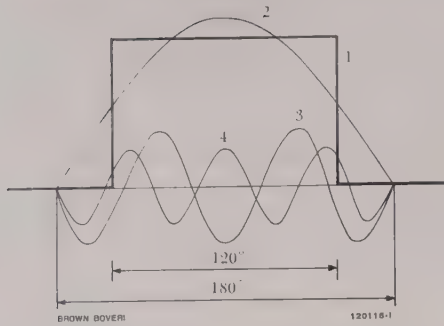


Fig. 3. — Wave-form of the mains current for a hexapulse circuit with the primary winding of the converter transformer connected in delta

- 1 = Mains current
- 2 = Fundamental wave of the mains current
- 3 = Fifth harmonic of the mains current
- 4 = Seventh harmonic of the mains current

Following this recapitulation of the basic principles of the polyphase converter as a static switching element, the main factors responsible for the production of the reactive power will be examined. The example of the simple hexapulse circuit shown in Fig. 2 will be used, and from the diagrams the mains current in phase *R*, the curve of the anode voltages and the direct current are taken over. The composition of the d.c. from rectangular blocks may be adopted, assuming the transformer is free from leakage and the direct current is ideally smoothed by a cathode reactor of infinite capacity. In this case the fundamental of the primary current and the primary voltage are in-phase.

Due to the various reactances X_b on the a.c. side, among which that of the converter transformer plays a very important part, the commutation of the individual anode currents does not take place instantaneously, but lasts a certain time. The higher the impedance voltage of the transformer and the larger the system reactances, and the heavier the operating current of the converter, the longer this time is. To explain the conditions during the change from one anode to the next by the current, the case of simple commutation will be assumed, i.e. outside the commutation period only one anode shall carry current, and during this period only two anode currents shall flow. The various reactances on the a.c. side are regarded as a lumped anode reactor. The

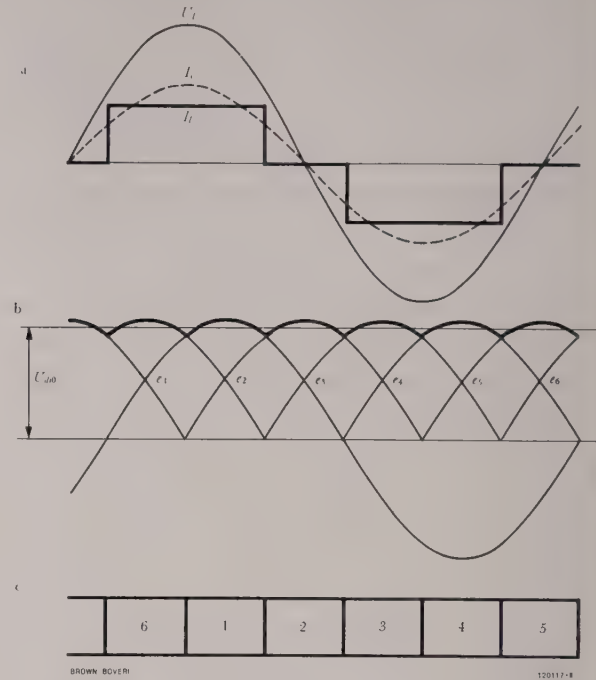


Fig. 4. — Currents and voltages of a hexapulse system with respect to time, for uncontrolled operation, not allowing for line inductances

- a: Line side
 - U_L = Phase voltage
 - I_L = Mains current
 - I_1 = Fundamental of mains current
- b: D.C. voltage
 - e_1-e_6 = Secondary phase voltages
 - U_{d0} = Mean d.c. voltage
- c: Formation of the direct current by combination of successive anode currents

direct current on the d.c. side is again assumed to be ideally smoothed, an assumption which applies to all subsequent cases considered.

The current changeover is illustrated in Fig. 5: On changing from anode 1 to anode 2, the second anode fires while the arc is still burning on anode 1. Thus the two anodes are connected through the arc and the momentary difference in the anode voltage drives a short-circuit current, which is only limited by the lumped anode reactor. This short-circuit current builds up the current at anode 2 and reduces that at anode 1 to zero. This phenomenon, which takes place between t_1 and t_2 , is known as overlapping. Its duration is measured in electrical degrees and

referred to as the angle of overlap u_a . At full voltage, i.e. when the delay $\alpha=0$, the value of u_a is u . Since the short-circuit current is sinusoidal, the build-up and drop of the anode current follows part of the sine wave. The maximum value the overlap can attain with simple commutation, before a third anode can take over the current-carrying duty, is shown in Table III.

TABLE III			
p	3	6	12
u_m	120°	60°	30°

Commutation, i.e. the overlapping of the anode currents, assuming for the time being that the converter is uncontrolled, causes an additional drop in the d.c. voltage, due to the elimination of the voltage-time area shown hatched in Fig. 5. This drop is due to the reactances on the a.c. side and is denoted by D_x , the inductive d.c. voltage drop. At the same time the theoretically rectangular wave-form of the anode current flattens out, a deformation which affects the stepped form of the mains current; the larger the angle of overlap becomes, the nearer the current wave-form approaches the sine wave. The inductive d.c. voltage drop D_x reduces the ideal no-load d.c. voltage U_{d0} to the mean d.c. voltage U_d . It is common practice to refer this voltage drop to the ideal no-load d.c. voltage and express it as a percentage. The figure thereby obtained is known as the percentage d.c. voltage drop d_x ; this is a specific voltage drop for which the following equation applies:

$$d_x = \frac{D_x}{U_{d0}} \cdot 100 = 1 - \frac{U_d}{U_{d0}} \cdot 100 = \frac{1}{2} (1 - \cos u) \cdot 100$$

(2)

The larger the reactances on the a.c. side and the larger the service current of the converter, the greater the overlap. In uncontrolled operation the following expression applies

$$\frac{1}{2} (1 - \cos u) = \frac{X_b I_d}{2\sqrt{2} U_{v0} \sin \frac{\pi}{p}}$$

(3)

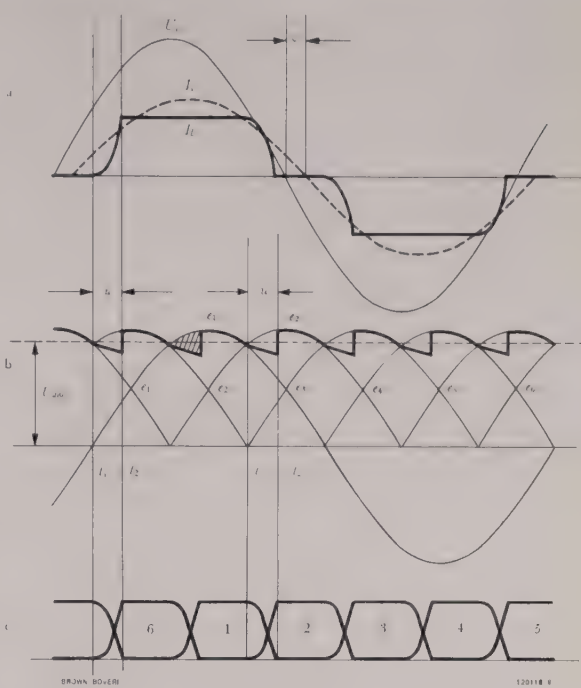


Fig. 5. - Currents and voltages of a hexapulse system with respect to time, for uncontrolled operation; explanation of overlap

- a: Line side
 U_L = Phase voltage
 I_L = Mains current
 I_1 = Fundamental of mains current
 φ = Displacement between phase voltage and fundamental wave of the mains current
- b: D.C. voltage
 $e_1 - e_6$ = Secondary phase voltages
 U_{d0} = Mean d.c. voltage
 t_1 = Start of overlap
 t_2 = End of overlap
 u = Overlap angle
- c: Formation of the direct current by combination of successive anode currents

As may be seen from Fig. 5, the overlap causes a phase displacement φ between the fundamental of the mains current and the mains voltage. This gives rise to a further component of the reactive load, the reactive power of commutation.

The curves of the voltages and currents in the grid-controlled converter, allowing for line inductances and assuming an infinitely large inductance in the d.c. circuit, are shown in Fig. 6. The mean d.c. voltage in terms of the delay angle α is given by

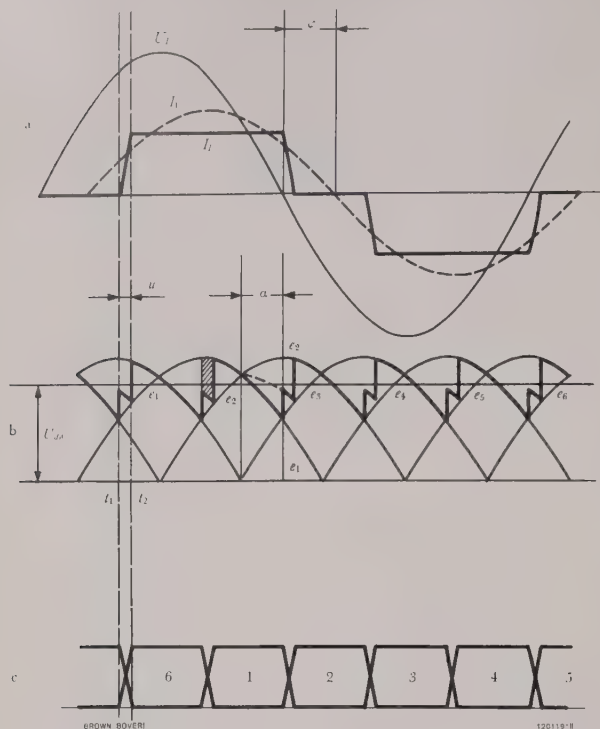


Fig. 6. — Currents and voltages of a hexapulse system with respect to time, for controlled operation

- a: Line side
 U_L = Phase voltage
 I_L = Mains current
 I_1 = Fundamental of mains current
 φ = Displacement between phase voltage and fundamental wave of the mains current
- b: D.C. voltage
 e_1-e_6 = Secondary phase voltages
 U_{d0} = Mean d.c. voltage
 t_1 = Start of overlap
 t_2 = End of overlap
 u = Overlap angle
- c: Formation of the direct current by combination of successive anode currents

$$U_{d0} = U_{d0} \cdot \cos \alpha \quad (4)$$

In Fig. 6 the momentary values of the anode voltages and currents are marked. During the commutation period, we now have

$$\frac{e_1 - e_2}{2} = \frac{X_b}{\omega} \frac{di}{dt} \quad (5)$$

while, for the instant $\omega t = -\pi/p + u$ we may write

$$\cos \alpha - \cos (\alpha + u) = \frac{X_b I_d}{\sqrt{2} U_{v0} \sin \frac{\pi}{p}} \quad (6)$$

If the same service current is assumed for the equations (3) and (5), the expressions on the left-hand sides can be equated, thereby giving the following expression for the angle of overlap

$$u = \cos^{-1} (\cos \alpha + \cos u_0 - 1) - \alpha \quad (7)$$

This implies that the overlap u decreases with growing delay of the firing point. This may be explained by the fact that, owing to the abrupt change in voltage to the succeeding anode voltage, the following anode current begins with a finite initial tangent. The greater the delay α of the firing point, the nearer the anode current during the commutation period approaches a linear rate of rise.

From Fig. 6 it will be observed that the momentary d.c. voltage drop is given by half the difference between the two anode voltages concerned, i.e. $\frac{1}{2}(u_2 - u_1)$. Since no other inductive drop occurs, outside the commutation period, the d.c. voltage drop d_x , expressed as a percentage of the no-load voltage is given by

$$d_{xa} = \frac{\cos \alpha - \cos (\alpha + u)}{2} \quad (8)$$

The absolute inductive d.c. voltage drop is independent of the degree of control of the converter. Applied to the two diagrams in Fig. 5 and 6, this denotes the same area as that of the hatched area below the voltage-time curves.

The inductive component of the d.c. voltage drop d_x is largely determined by the impedance voltage e_x of the converter transformer. For a particular connection there is a definite relationship between these two quantities. Since the absolute inductive voltage drop is independent of the degree of control of the converter, the figures given in Table IV apply to both uncontrolled and controlled converters.

TABLE IV

$\frac{d_x}{e_x}$	1.5	0.5*	0.5

* With complete linkage of the secondary winding.

In the grid-controlled converter the firing delay and overlap cause the anode current to be displaced with respect to the anode voltage. The result of this is that the fundamental of the current on the line side lags behind the voltage, giving rise to reactive power.

In addition to the reactive load components due to the grid control and overlap, there comes a third component, the reactive power of the transformer at no-load. This consists of the magnetizing reactive power, which is almost independent of the load. If the ratio of magnetizing current to the primary current on-load, or to the direct current I_d is denoted by κ and the ratio at full-load or at I_{d1} by κ' , we may write

$$\kappa = \kappa' \frac{I_{d1}}{I_d} \quad (9)$$

To Estimate the Power Factor of a Converter Installation

Owing to the primary current not being sinusoidal, the power factor of a converter installation is not equal to the cosine of the phase displacement; a distinction must be made between the power factor λ and the displacement factor $\cos \varphi$. These two factors are defined (IEC Publ. 84, 1957) as follows:

$$\text{Total power factor } \lambda = \frac{\text{active power}}{\text{apparent power}} = v \cos \varphi$$

$$\begin{aligned} \text{Displacement factor } \cos \varphi &= \\ &= \frac{\text{active power of fundamental wave}}{\text{apparent power of fundamental wave}} \end{aligned}$$

$$\text{Distortion factor } = v$$

The total power factor would be the governing factor if the converter were the sole load on the supply system; in practice the deciding factor is the power factor of the fundamental wave of the current. The displacement factor of a converter installation, allowing for grid control, inductances on the line side and the no-load current, is given by the following expression

$$\cos \varphi = \cos \left[\tan^{-1} \frac{\frac{2u + \sin 2\alpha - \sin 2(\alpha + u)}{4 [\cos \alpha - \cos (\alpha + u)]} + \frac{\kappa}{v}}{\frac{1}{2} [\cos \alpha + \cos (\alpha + u)]} \right] \quad (10)$$

From the preceding chapter we now know all the quantities occurring in the above expression. Whereas the delay angle α , the percentage magnetizing current κ and the distortion factor v are fixed for a definite degree of control and circuit arrangement, the overlap u is a function of the delay α , the inductive voltage drop d_x and the load I_d/I_{d1} :

$$u = f \left(\alpha, d_x, \frac{I_d}{I_{d1}} \right) \quad (11)$$

To provide a rough estimate of the displacement factor when a quick calculation has to be made, the two expressions (10) and (11) are shown graphically in Fig. 7 and 8.

As an example a reversing blooming mill is considered, having a cut-out torque of 300 mt, a basic speed of 40 rev/min and an effective power of 4500 kW. At an armature voltage of 1300 V the rated current is assumed to be 4800 A. The voltage drops at rated current are the armature voltage drop of 80 V, the drop D_{rt} of 20 V due to copper losses in the transformer, the arc voltage D_c of 25 V in the converter and finally the impedance voltage $e_x = 10\%$. On the assumption that the inductive d.c. voltage drop is largely determined by the impedance voltage, it follows from Table IV for the connection with interphase transformer that $d_x/e_x = 0.5$. The no-load voltage satisfying the condition that, at 300 mt—corresponding to 2.75 times the rated current—the terminal voltage should be 1300 V, is then calculated as follows:

$$\begin{aligned} U_{d0} &= U_d \left[1 + \frac{I_d}{I_{d1}} \times 0.5 \times e_x \right] + \frac{I_d}{I_{d1}} \times D_{rt} + D_c \\ &= 1300 (1 + 2.75 \times 0.5 \times 0.1) + 2.75 \times 20 + 25 \\ &= 1560 \text{ V} \end{aligned}$$

The apparent power corresponding to this case becomes

$$2.75 U_{d0} I_{d1} = 1560 \times 4800 \times 2.75 \text{ VA} = 20.5 \text{ MVA}$$

In order to produce a current of $2.75 I_d$ at standstill, the delay must be so large that the voltage amounts to $1560 - 1300 = 260$ V. This corresponds to a delay of

$$\cos \alpha = 260/1560 = 0.166$$

giving a delay angle of $\alpha = 80^\circ$.

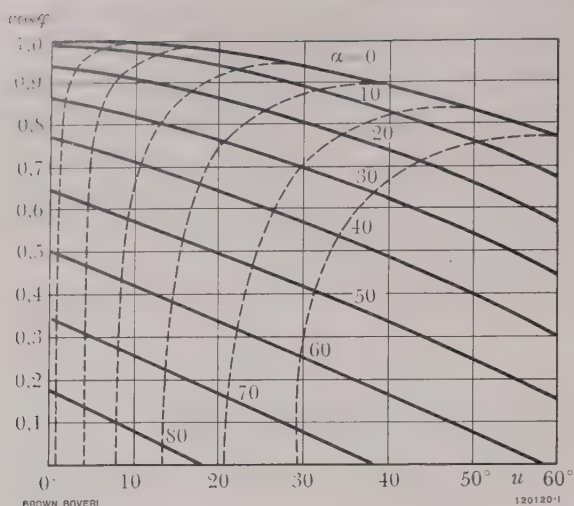


Fig. 7. — Displacement factor $\cos \varphi$ of a converter with any pulse number, allowing for line inductances but ignoring the no-load current of the transformer

$\cos \varphi$ = Displacement factor
 α = Delay angle
 u = Angle of overlap

From the curve in Fig. 8, for an inductive voltage drop of $0.5 \cdot e_x \cdot 2.75 = 0.137$, we obtain an overlap $u = 8^\circ$, while from Fig. 7 a displacement factor of $\cos \varphi = 0.1$ is obtained. Thus the reactive load surge which may be anticipated works out to $20.5 \sin \varphi = 20.5 \times 0.994 = 20.4$ MVar.

Thus to introduce the ingot at half the basic speed, the electromotive force of the armature must amount

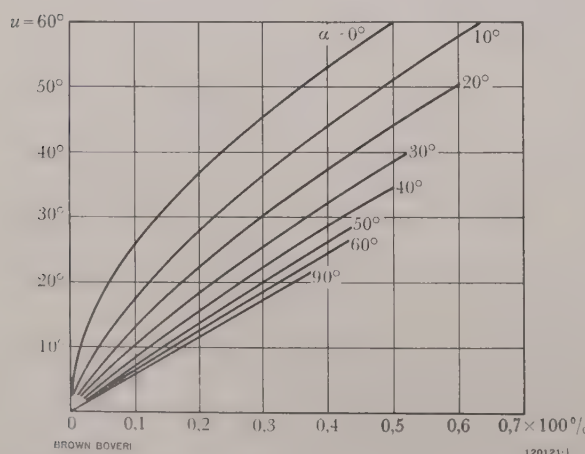


Fig. 8. — Angle of overlap u as a function of the inductive voltage drop at service current, and of the delay angle α ; connection with interphase transformer

$e_x \frac{I_d}{I_{d1}}$ = Inductive voltage drop at service current

to $0.5(1300 - 80) = 610$ V. Accordingly the terminal voltage is

$$U_{di0\alpha} = 610 + 2.75 \times 80 + 2.75 \times 20 \\ + 1560 \times 2.75 \times 0.5 \times 0.1 + 25 = 1125 \text{ V}$$

From this the voltage reduction and delay angle work out to

$$\cos \alpha = \frac{1125}{1560} = 0.72; \quad \alpha = 44^\circ.$$

The overlap has risen to 11° and, from Fig. 7, the displacement factor $\cos \varphi_1 = 0.65$. Hence the reactive load surge amounts to $20.5 \sin \varphi_1 = 20.5 \times 0.73 = 15.0$ MVar.

To Estimate the Voltage Dip in the Mains Caused by Inductive Load Surges

The heavy load surges caused by reversing blooming mills, though short in duration, follow in quite a rapid succession and have a very rapid rate of rise. Owing to the very strict stipulations made regarding the reversing times of blooming mills, the rate of rise of the current is often very near the limit permissible for the armatures of d.c. machines. The resultant rate of rise of reactive power in the mains can thus amount to as much as 10 MVar per 100 ms.

The effect of such load surges on the service voltage will now be discussed with reference to Fig. 9. Imagine all power generating machines to be lumped in a single equivalent generator, whose air-gap voltage—i.e. the voltage after the transient reactance—should be so rigid that it does not change when such a load surge is experienced. This generator is assumed to feed into the mains of a rolling mill through a resultant active resistance R and a resultant reactance X . How high the voltage at the generator must be to maintain constant voltage at the busbars with a load current assumed to be constant and denoted by I , is shown by the vector diagram in Fig. 9b. If a further load surge is experienced, with a predominantly inductive component in the current, the voltage at the busbars drops abruptly to the value U_{Ls} . From the vector diagram in Fig. 9c it will be seen that the voltage dip depends mainly on the surge current and the total impedance $X + X'_d$ of the supply system. At the basic load there is an

appreciable quadrature voltage drop δU in addition to the direct-axis drop ΔU . This necessitates displacement of the voltage vector. With inductive load surges only the direct-axis voltage drop is important; the quadrature drop can be ignored. The voltage dip caused by a reactive load surge is given by the following equation

$$\Delta U = I[\cos \varphi \cdot R + \sin \varphi \cdot (X + X'_d)]$$

Since, as stated already, the most important factor is the mains voltage drop caused by the reactive component of the surge current and the total impedance, the first term in the above equation can be ignored. The equation then takes the form

$$\Delta U = I(X + X'_d)$$

It contains those quantities principally concerned with the estimation of the short-circuit current.

By definition the short-circuit current is the current that causes a 100 % voltage dip (or complete collapse). Since the surge current and short-circuit current are roughly in phase with one another, the voltage drops they cause will likewise be almost in phase. Thus, however, the following statement is permissible: The magnitude of the percentage voltage dip caused by an inductive load surge corresponds to the percentage share of this surge current in the short-circuit current, i.e.

$$\Delta U = \frac{I}{I_k} \cdot 100 \%$$

The second part of the task of estimating the voltage dip caused by inductive load surges therefore consists of the determination of the short-circuit current at the relevant point in the system.

Generators:
$$X'_d = \frac{x'_d \cdot U_n^2}{P_n} \cdot 10^{-2}$$

Transformers:
$$X_d = \frac{x_t \cdot U_n^2}{P_n} \cdot 10^{-2}$$

Lines:
$$X = \omega L$$

- where
- X = reactance in ohm
 - x'_d = transient reactance in %
 - x_t = short-circuit reactance in %
 - U_n = nominal line voltage in kV
 - P_n = rated power in MVA
 - ω = frequency of rotation $\approx 314 \text{ s}^{-1}$ at 50 c/s
 - ωL = reactance of the line = 0.4 ohm/km

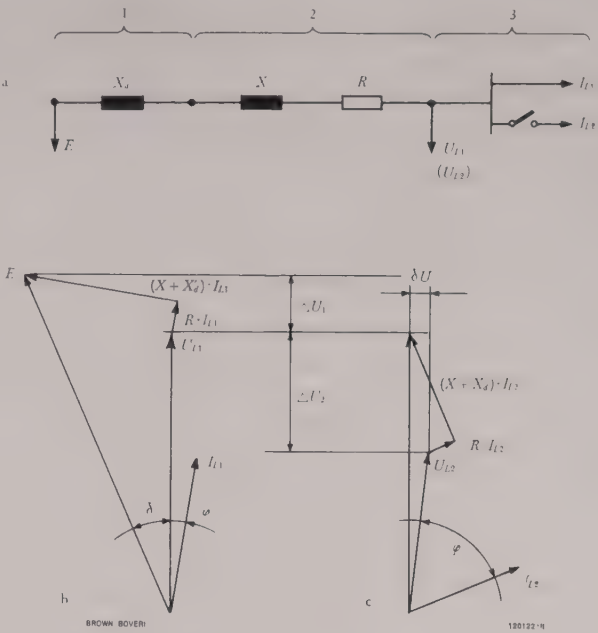


Fig. 9. – Equivalent circuit diagram and vector diagram for example calculated

- a: Equivalent circuit diagram
 - 1 = Equivalent generator
 - 2 = Supply system
 - 3 = Load
 - E = Air-gap voltage
 - X'_d = Transient reactance
 - X = System reactance
 - U_{L1}, U_{L2} = Voltages at loads
 - I_{L1}, I_{L2} = Currents at loads
 - δ = Load angle
 - φ = Phase angle
 - b: Vector diagram for predominantly resistive load
 - c: Vector diagram for predominantly inductive additional load
- $\Delta U_1, \Delta U_2$ = Direct-axis voltage drop
 δU = Quadrature voltage drop

With the aid of the example shown in Fig. 10 the method of determining the short-circuit currents at various points in a given system will be demonstrated. The system resistances will be determined by utilizing the percentage voltage drops, and all reactance referred to 10 kV, for which

$$X_{red10} = X \left(\frac{10}{U} \right)^2 = \frac{x \cdot U^2}{P_n} \cdot 10^{-2} \cdot \left(\frac{10}{U} \right)^2 = \frac{x}{P_n}$$

in which x denotes the transient reactance of the generator or transformer and P_n the rated power of the generator or transformer in MVA. The short-circuit

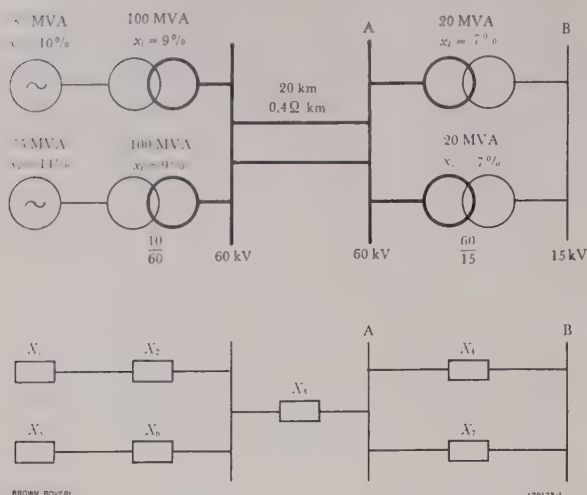


Fig. 10. — Single-line circuit diagram and equivalent circuit diagram for example calculated

x_d = Transient reactance of the generators

x_t = Short-circuit reactance of the transformers

X_1 – X_7 = Equivalent reactances referred to 10 kV

A, B = Points in the system for which the short-circuit currents have to be calculated

current is calculated from the following formula:

$$I_k = \frac{U_n}{\sqrt{3} X} \quad [\text{kA}]$$

For this particular calculation the short-circuit current is first calculated with respect to 10 kV and then converted for the relevant service voltage:

$$I_{10} = \frac{10}{\sqrt{3} X_{red10}} = \frac{5.78}{X_{red10}} \quad [\text{kA}]$$

$$I = I_{10} \frac{10}{U_n} \quad [\text{kA}]$$

Below the single-line diagram in Fig. 10 the equivalent circuit diagram is given, for which the various system reactances have to be determined:

$$X_1 = \frac{10}{80} = 0.125 \Omega$$

$$X_2 = \frac{9}{100} = 0.09 \Omega$$

$$X_3 = \frac{20}{2} \times 0.4 \left(\frac{10}{60} \right)^2 = 0.11 \Omega$$

$$X_4 = \frac{7}{20} = 0.35 \Omega$$

$$X_5 = \frac{14}{75} = 0.19 \Omega$$

$$X_6 = \frac{9}{100} = 0.09 \Omega$$

$$X_7 = \frac{7}{20} = 0.35 \Omega$$

The resultant reactances at the points A and B are thus:

$$X_A = 0.23 \Omega \quad X_B = 0.405 \Omega$$

from which the short-circuit currents with respect to 10 kV are

$$I_{A10} = \frac{5.78}{0.23} = 25 \text{ kA}$$

$$I_{B10} = \frac{5.78}{0.405} = 14.3 \text{ kA}$$

Finally, from these, the true short-circuit currents and the breaking capacities that must be provided are

$$I_A = 25 \frac{10}{60} = 4.2 \text{ kA} \quad P_A = 440 \text{ MVA}$$

$$I_B = 14.3 \frac{10}{15} = 9.5 \text{ kA} \quad P_B = 250 \text{ MVA}$$

As explained at the beginning of this chapter, the voltage dip can be estimated by dividing the surge load by the short-circuit capacity.

Synchronous Capacitors Excited by Converters

Special converter connections, such as that with asymmetric grid control, the series connection and zero-anode control allow the reactive power of the converter-fed drive to be reduced, thus lowering the voltage dips in the supply system. Nevertheless there still remain the frequently repeated, though small reactive load surges which cannot be corrected by ordinary voltage regulators. It is possible to eliminate the dips by compensating for the suddenly increased demand for reactive power by equally rapidly supplying reactive power at the input to the load. An ideal means of doing this is the synchronous capacitor.

The employment of a synchronous capacitor with reactive power control is illustrated in Fig. 11. From the current and voltage on the load side the desired value for the reactive power is formed. The rapidly variable reactive load component is compared

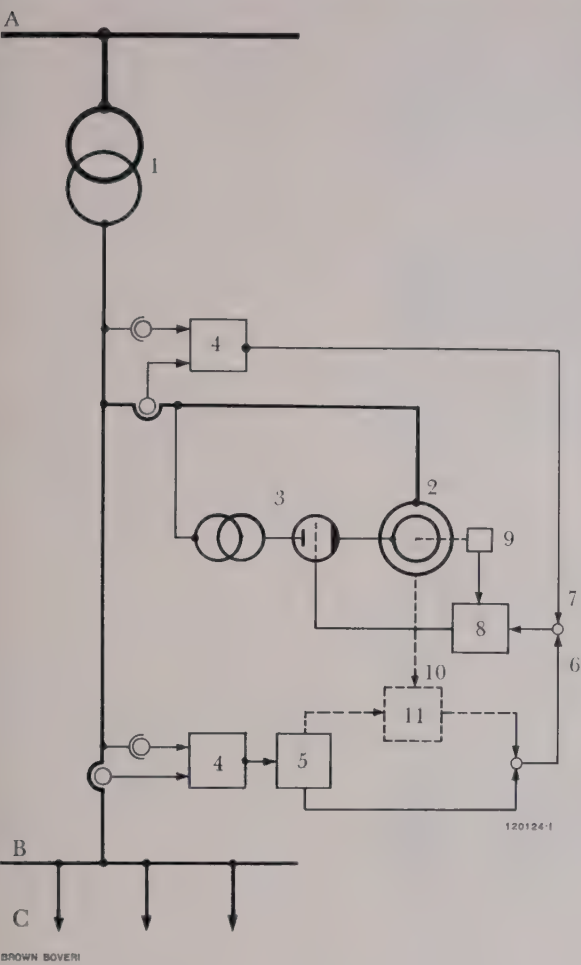


Fig. 11. - Synchronous capacitor with converter excitation

- A = National grid
- B = Steelworks power system
- C = Loads
- 1 = Supply transformer
- 2 = Synchronous capacitor
- 3 = Excitation by converter
- 4 = Power transducer
- 5 = Component resolver
- 6 = Desired value of reactive power
- 7 = Actual value of reactive power
- 8 = Regulator
- 9 = Measurement of load angle
- 10 = Winding temperature
- 11 = Limiter for desired value

directly with the power value given by the actual current and voltage at the infeed point of the synchronous capacitor. Every deviation of the actual from the desired value acts through the reactive power regulator on the converter, and thus varies the excitation of the synchronous capacitor. If the

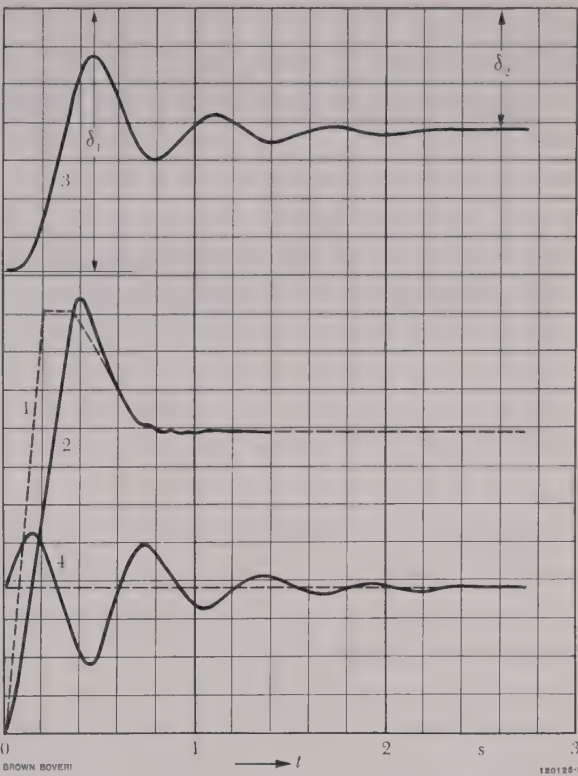


Fig. 12. - Synchronous capacitor with active (base) load; application of a reactive load

- 1 = Desired value of reactive power
- 2 = Actual value of reactive power
- 3 = Load angle
- 4 = Active power
- δ_1 = Load angle before application of reactive load
- δ_2 = Load angle at constant reactive load
- t = Time scale in s

reactive load peaks do not tax the machine to the limit of its thermal capacity, it may also be employed to provide the slow changes in reactive power determined by the component resolver.

The rotor, energized by the excitation current, is made to rotate in synchronism with the stator field, but lags by the load angle δ as it has to make good the friction losses. The torque is proportional to the sine of this angle. If the magnitude of the rotor field is changed by super-excitation, while the friction or load torque remains the same, the load angle must change slightly. Owing to its mass, the rotor will "hunt" relative to the synchronous stator field. To obtain the necessary damping, a quantity proportional to the change in the load angle is introduced into the control loop.

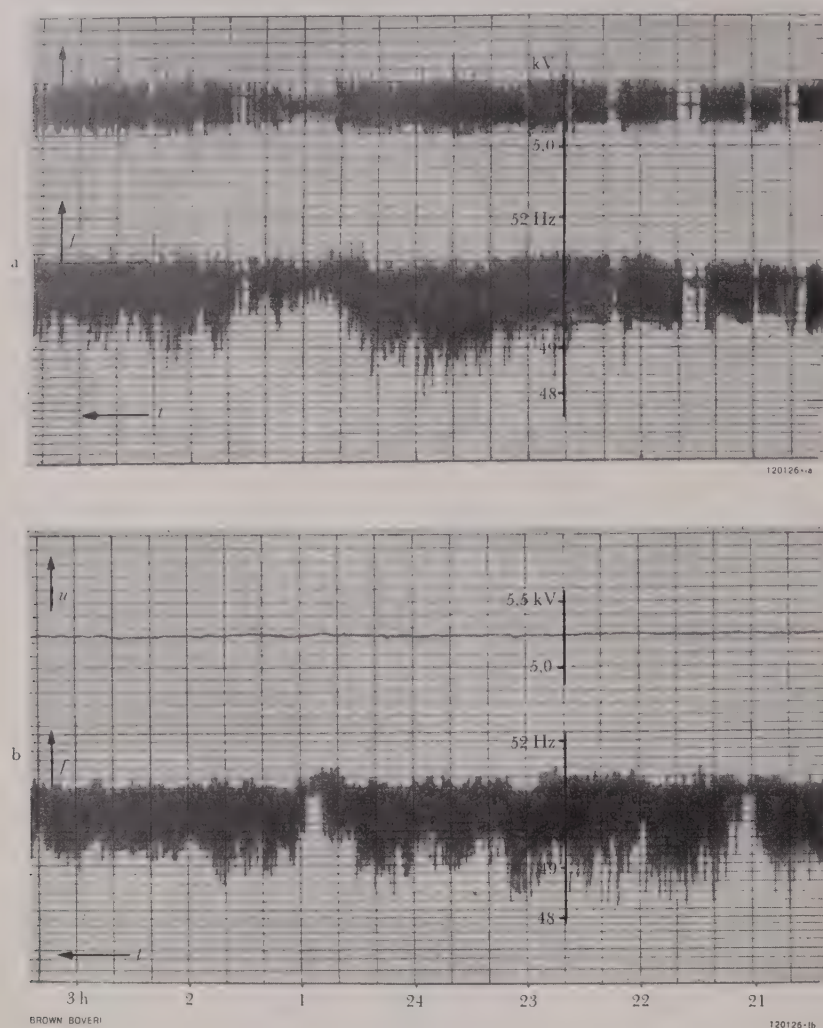


Fig. 13. — Oscillograms of voltage and frequency in a steelworks during rolling

a: Excitation by main and pilot exciters

b: Excitation by static converter

u = Mains voltage

f = Mains frequency

t = Time

This device is particularly important in those cases where the synchronous machine, in addition to providing reactive power, also has to provide an active output at the shaft, as is the case when synchronous motors are used to drive compressors. The diagram in Fig. 12 shows part of an investigation performed on a digital computer. A synchronous motor driving a compressor at constant power through gearing is forced to give up reactive power at the moment $t=0$. The curve shows the variation of the desired value, curve 2 the actual value. The load angle, whose value was δ_1 before application of the reactive load, attains the new steady state after a few oscillations due to the change in the rotor field. During the period in which the load angle changes from δ_1 to the new position δ_2 , there is a certain amount of hunting by the active power at the shaft.

The success achieved by employing converter-excited synchronous capacitors is well illustrated by the oscillograms in Fig. 13, recorded in a steelworks under identical loading conditions. When an exciter machine was used, voltage dips of up to 7% were experienced; when a grid-controlled converter with electronic reactive power control is employed, this figure is reduced to 0.5%.

Synchronous capacitors excited by electronically controlled mercury-arc converters are ideal for compensation of reactive load peaks occurring frequently and in quick succession. In some steelworks, which generate their own power or are situated at the end of a long transmission line, their employment was essential to the adoption of converter-fed d.c. motors for heavy reversing drives.

(KME)

H. KUNTNER

THE NEW SINGLE-ANODE MUTATORS WITH VAPOUR JACKET

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By incorporating a new component in the new single-anode mutators (mercury-arc converters), their surge load capacity in pulsating operation has been greatly improved and, at the same time, the range of working temperatures extended without having to resort to temperature regulation, heating or filling with rare gas.

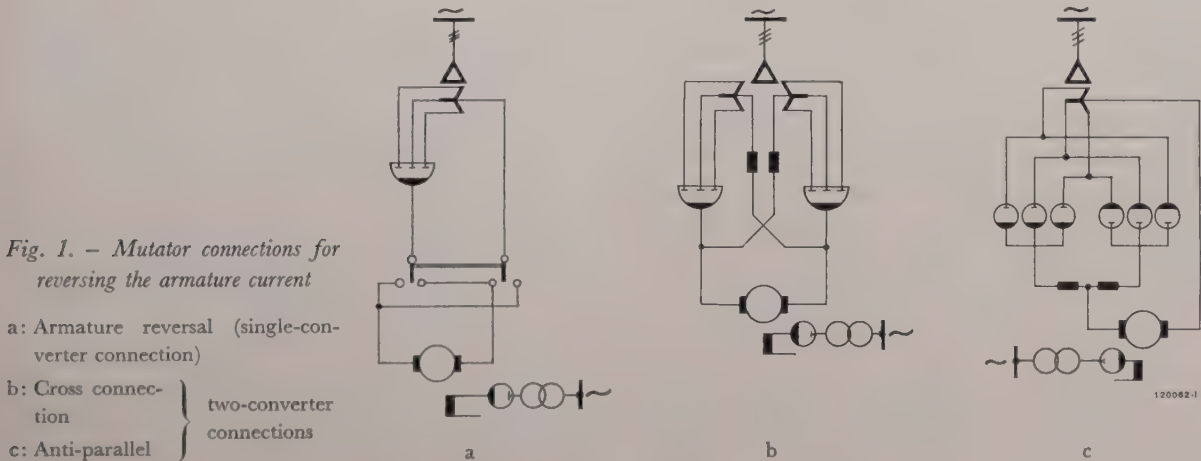
Development Trends

HAVING regard to the need for maximum versatility, the new mercury-arc converters (single-anode mutators) were developed primarily to meet the requirements of their main sphere of application, namely for feeding industrial drives. Here reversing drives make the heaviest demands on the tanks. Development trends will therefore be studied with particular reference to this kind of operation.

A reversing drive has to produce a torque in either direction. With a d.c. motor this can be done by reversing the armature current (Fig. 1 a, b, c) or the field current (Fig. 2). For reversing the armature current mechanical reversing switches used to be commonly used—as shown by the circuit diagram in Fig. 1 a—designed for frequent operation at zero

current. With control by motor field reversal a single-converter connection is also used, in contrast to two-converter connections with one rectifier for each direction of the armature current (Fig. 1 b, 1 c), which reduces the cost of the armature circuit owing to the smaller number of mutators and switches. The use of the two-converter connection was restricted owing to its needing twice as many tanks for the heavy-current armature circuit as the single-converter connection. When multi-anode tanks are employed it is also impossible to adopt the anti-parallel connection because there is only one cathode common to the six anodes. In that case the cross connection has to be used, involving a greater outlay for transformers since a separate secondary winding is needed for each direction of the current.

To obtain an outlay comparable to that for the anti-parallel connection with the excellent dynamic properties of a two-converter connection, not only as regards the transformer but also the converters, it was necessary to devise tanks with a higher surge load capacity. In the single-converter connection the surge current and mean value of the current of the



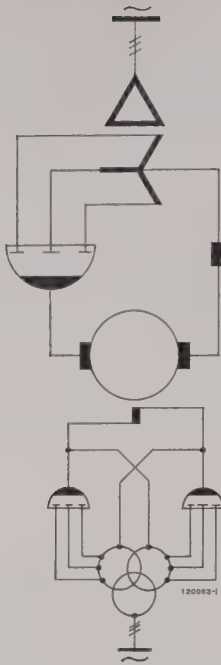


Fig. 2. — Mutator connection for field reversal (single-converter connection), field supply in cross connection to reverse the field current

rectifier set corresponds to that of the motor, whereas in the two-converter connection the mean value per set drops to half the mean motor current. Thus the ratio of the surge current to the mean value is twice as high with the two-converter connection as with the single. In the majority of drives the motor is expected to be able to carry up to double the rated current. In other words, in the two-converter connection the mutators have to be able to withstand a surge four times as high.

Hence, if mutators can be made to withstand a surge equal to four times the rated current, they may be employed in the two-converter connection at their full rated current. The number of tanks is then only determined by the rated current of the motor divided by the rated current of each tank. Since the motor current is always the same, in either the single or two-converter connection, the number of tanks remains the same.

The rated current of the motor is an r.m.s. value, on account of the losses being proportional to the square of the current; the rating of the mutator, on the other hand, is an arithmetic mean value. However, this difference need not be taken into account

because, with the rapid pass sequence, the arithmetic mean tends to approach the r.m.s. value. Therefore, as described above, the number of tanks is usually determined by dividing the rated current of the motor by that of each mutator.

In order that the same number of tanks may be used in anti-parallel as with the field-reversal connection, assuming equal transformer rating and impedance voltage, it must be stipulated that the tanks, when operating at zero voltage, shall be capable of withstanding twice the anode blocking duty¹ [1]. The initial inverse voltage does not change, but the rate of change of the current is doubled, because the circuit has to manage with only half the number of tanks per direction.

Apart from increasing the surge load capacity in this way in order to cheapen the extremely responsive anti-parallel circuit, one of the main aims of the development programme visualized was to extend the rather narrow range of temperatures in which the mutators had hitherto been obliged to operate. Previously, particularly with heavy load surges, it was necessary to keep the temperature to within 10 °C, which could be barely be doubled by employing a rare-gas filling, because the greater gas pressure, though extending the range downwards, simultaneously lowers the upper limit. For this reason quite extensive supervisory, control and heating elements were needed to maintain the desired temperature in the mutator, some of which were replaced or augmented by air-conditioning the room in which the mutators were installed.

In order to meet these two main requirements, i.e. increasing the surge load capacity and extending the temperature range, it was necessary to adopt a completely new approach. This will now be explained by comparing the distribution of the vapour density in the new tanks with vapour jacket with that in one of the former type (with saturated vapour). The well-known advantages of single-anode tanks, i.e. easy storage of spares, ability to adopt the compact metalclad design including all auxiliaries, etc., will be dealt with in the final chapter.

¹ Admittedly the duration of the load with antiparallel connection is only half as long as with field reversal. This reduction of the duty period does not greatly affect the necessary anode blocking duty.

Vapour Density Distribution in Condensation Vessels

In the mutators employed hitherto the vapour density was determined by the temperature of the wall on which it could condense. However, only in the cold, unloaded state is the gas density in the tank exactly equal to the saturated vapour concentration corresponding to the tank temperature:

$$\begin{aligned} n_s &= 0.972 \times 10^{19} \frac{p_s}{T_s} \\ &= 0.972 \times 10^{19} \frac{10^{9.48 - \frac{1}{2} \log T_s - \frac{3300}{T_s}}}{T_s} \end{aligned} \quad (1)^2$$

On load and when the cathode is warm, a certain quantity of condensate

$$M_c = m_{\text{Hg}} Z_c$$

where M_c is in g/cm²s and Z_c is in molecules/cm², has to be transferred to the wall, flowing down it to the cathode and thus closing the circuit.

According to the kinetic theory of gases and the Maxwell velocity distribution, the amount striking the wall per cm² and second is

$$Z_D = \frac{n_D}{4} w_{mD} = \frac{1}{\sqrt{2\pi}} \sqrt{\frac{k}{m_{\text{Hg}}}} n_D \sqrt{T_D} \quad (2)$$

Only a very small proportion is retained as condensate, the remainder β is reflected. On the other hand, molecules are emitted by the condensate on the wall, the maximum number being

$$Z_F = \frac{n_F}{4} w_{mF} = \frac{1}{\sqrt{2\pi}} \sqrt{\frac{k}{m_{\text{Hg}}}} n_F \sqrt{T_F} \quad (3)$$

Here too the greater part β is reflected (e.g. by impurities [2]), so that only the fraction $(1-\beta)$ enters the vapour space. The resultant amount of condensate given by equations (2) and (3) may be expressed in molecules per cm² and second by

$$\begin{aligned} Z_c &= (1-\beta)(Z_D - Z_F) = (1-\beta) \left(n_D \frac{w_{mD}}{4} - n_F \frac{w_{mF}}{4} \right) \\ &= \frac{(1-\beta)}{\sqrt{2\pi}} \sqrt{\frac{k}{m_{\text{Hg}}}} \left[n_D \sqrt{T_D} - n_F \sqrt{T_F} \right] \end{aligned} \quad (4)$$

or in g/cm²s by

$$M_c = m_{\text{Hg}} Z_c = \frac{(1-\beta)}{\sqrt{2\pi}} \sqrt{m_{\text{Hg}} \cdot k} \left[n_D \sqrt{T_D} - n_F \sqrt{T_F} \right] \quad (5)$$

The directed rate of flow of the vapour which causes a deviation from the Maxwell distribution can be ignored for the condensation vessels used hitherto, because it is two orders of magnitude smaller than the mean thermal velocity in the temperature range considered. The amount of condensate M_c to be transferred from the vapour at the temperature T_D to the condensate at the temperature T_F depends on the magnitude of the current and temperature of the cathode.

The amount of vapour produced by the cathode comprises one fraction governed by the current and another fraction dependent on the cathode temperature, according to measurements made by Issendorf [3]. The latter fraction D_T can be expressed, in accordance with the relationship for evaporation into the vacuum, analogous to equations (2-4),

$$\begin{aligned} Z &= (1-\beta) n_s \frac{w_{ms}}{4} \\ &= (1-\beta) \frac{1}{\sqrt{2\pi}} \sqrt{\frac{k}{m_{\text{Hg}}}} n_s \sqrt{T_s} \left[\frac{\text{molec.}}{\text{cm}^2 \text{ s}} \right] \end{aligned} \quad (6)$$

by

$$D_T = A_K (1-\beta_K) \sqrt{\frac{m_{\text{Hg}} k}{2\pi}} n_K \sqrt{T_K} = B n_K \sqrt{T_K} \text{ [g/s]} \quad (7)$$

i.e. by an exponential curve obtained from the product of the density of the saturated vapour and the square root of the corresponding saturation temperature. The fraction dependent on the current is composed of a fraction evaporating in the immediate vicinity of the cathode spot, and another yielded by the mercury spray which evaporates on the hot surface of baffles, etc. A second part of this mercury spray strikes the wall of the tank, without changing into vapour, or, if a large amount strikes a surface, the excess liquid mercury may drip before it has had time to evaporate completely, and thus finds its way back to the cathode. This second part, varying with the design, may be disregarded. For the first portion the coating of hot surfaces with mercury spray also varies with the design and can only be estimated very roughly. With a coating of

* For explanation of the various symbols, see appendix.

1 cm² the amount evaporated into vacuum, according to equation (6) and with a transmission coefficient of $\tau = (1 - \beta) = 0.1$, is about 0.56 g/cm²s at 200 °C. But the high rate of flow towards impact surfaces in the vicinity of the cathode, and the resultant pronounced deviation from the Maxwell distribution (see below) can no longer be disregarded. The mean thermal velocity

$$w_m = \sqrt{\frac{8kT}{m_{\text{Hg}}}} = \sqrt{\frac{8}{\pi} RT} \quad (8)$$

is only of the order of 10⁴ cm/s with very hot impact surfaces, whereas the rate of flow of jets of mercury vapour has been determined as being of the order of 10⁶ cm/s [4].

For the reasons mentioned, only a very small portion of the mercury spray, determined by Issendorf [3] to amount to 10.5 mg/As on the average, appears as vapour. With his arrangement he also measured precisely that portion of the mercury spray which struck the cathode container and flowed

directly back into the cathode. The total amount of mercury spray increases with the current (from 2 to 12 A rising from 9 to 15 mg/As). But since separate spots do not occur above 12–15 A [5 and p. 75 of 6] and the spot splits up at heavier currents, the specific amount may be assumed to have the value of 10.5 mg/As corresponding to the most frequent spot current of 5–7 A. This value may then be taken as constant over the entire current range.

When the mutator is switched on cold, the mercury spray first strikes the impact surfaces which are cold, and the proportion which evaporates may be considered negligible. In this case the amount proportional to the current f is at the most 1.3 mg/As. When the tank is warm from running, with certain designs, f must be increased, depending on the particular design, by the amount of spray which evaporates, namely $F > f = 1.3$ mg/As, so that according to equation (7) the total amount of vapour produced in the mutator is

$$D = FI + B n_K \sqrt{T_K} \text{ [g/s]} \quad (9)$$

This amount of vapour must condense on the condensation surface with the area A_c , which in water-cooled tanks may be regarded as being equal to the surface area of the cooled jacket.

$$\begin{aligned} M_c &= \frac{D}{A_c} = \frac{1}{A_c} (FI + B n_K \sqrt{T_K}) \\ &= (1 - \beta) \sqrt{\frac{m_{\text{Hg}} k}{2\pi}} \left[n_D \sqrt{T_D} - n_F \sqrt{T_F} \right] \end{aligned} \quad (10)$$

With the aid of the relationship for saturated vapour

$$n_D \sqrt{T_D} = f(T_D) \quad (11)$$

shown in Fig. 3 according to equation (1), the vapour temperature, can be determined from equation (10), and thus the density or also the pressure in accordance with equation (1)

$$\begin{aligned} n_D \sqrt{T_D} = f(T_D) &= \frac{1}{(1 - \beta)} \sqrt{\frac{2\pi}{m_{\text{Hg}} k}} \times \\ &\times \frac{1}{A_c} (FI + B n_K \sqrt{T_K}) + n_F \sqrt{T_F} \end{aligned} \quad (12)$$

For this the temperature T_K of the surface of the cathode and that of the condensate T_F has to be determined. In order to start from a constant

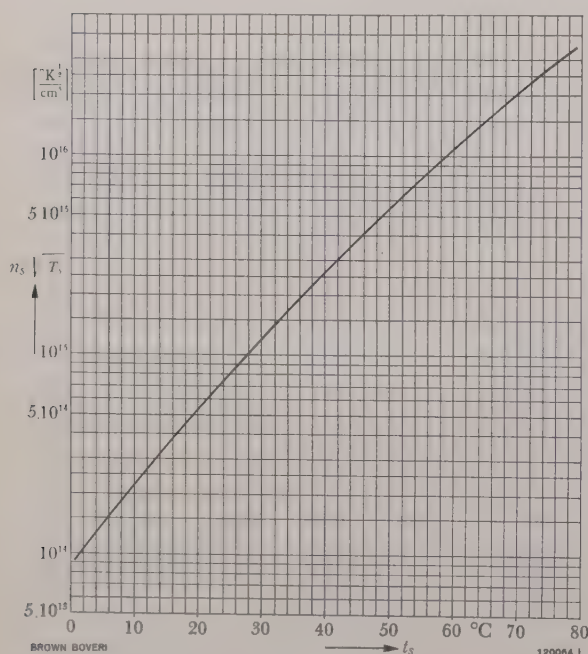


Fig. 3. — The product $n_s \sqrt{T_s}$ plotted to a logarithmic scale

$$n_s \times \sqrt{T_s} = 0.972 \times 10^{19} \frac{10^{9.48} - \frac{1}{2} \log T_s - \frac{3300}{T_s}}{\sqrt{T_s}}$$

n_s = Concentration of saturated mercury vapour

T_s = Temperature of saturated mercury vapour (°K)

t_s = Temperature of saturated mercury vapour (°C)

reference temperature in this respect, it is assumed that the tanks are cooled with water flowing at a constant rate. The transfer of heat from the surface of the mercury cathode right through to the cooling water is given by the heat transmission through the mercury $s_{\text{Hg}}/\lambda_{\text{Hg}}$, the transmission through the steel wall $s_{\text{Fe}}/\lambda_{\text{Fe}}$, and the transfer to the water in contact with the underside of the cathode container $1/\alpha_K$. Hence the temperature at the surface of the mercury is given by

$$T_K = T_W + \left(\frac{s_{\text{Hg}}}{\lambda_{\text{Hg}}} + \frac{s_{\text{Fe}}}{\lambda_{\text{Fe}}} + \frac{1}{\alpha_K} \right) q_K (T_K, I) \frac{I}{A_K} \quad (13)$$

The fraction of the losses dissipated by the cathode q_K was given by Bertele [7] as 1.5 W/A following measurements on large rectifiers [6, pp. 114 and 125]. However, this value is not constant, as it varies, on the one hand with the surface temperature of the cathode T_K and, on the other hand, with the current I and the temperature T_W of the cooling water; in fact with increasing current and water temperature the value of q_K diminishes. The major part of the cathode losses is dissipated by the work function of the electrons and the heat of evaporation of the mercury, and only a small remainder is conducted away by the mercury of the cathode [8]. The amount of mercury vapour, and thus the energy of evaporation, as shown in equation (9), is no longer proportional to the current at higher current or cooling-water temperature, as is often assumed. It increases exponentially with the current owing to the accompanying rise in the surface temperature of the cathode in the second term of equation (9). Likewise the heat of evaporation also increases with rising cooling-water temperature. Consequently, the remainder of the cathode losses, which have to be dissipated by the mercury, becomes steadily smaller with increasing current and cooling-water temperature. Having regard to equation (9), this explains why, in air-cooled tanks, the temperature of the cathode plates increases less than proportionally to the current, and only slightly when the flow of cooling air is reduced.

When the cathode temperature is low relative to the current, the second term in equation (9) can be ignored and q_K regarded as constant, i.e. the fraction $q_K I$ of the losses dissipated by the

mercury is proportional to the current. However, for single-anode tanks, whose cathode is completely covered by a baffle between it and the anode, the value of q_K must be assumed to be about 3 V because the cathode is bound to receive some of the waste heat radiated by the anode and transmitted by the baffle. The actual fraction of the anode losses varies with the design. Since the total anode loss power rises almost linearly with the current—to a first approximation—the fraction can be assumed to be proportional to the current. When the temperature of the mercury rises, an increasing proportion of this radiated energy from the anode is converted into heat of evaporation, the fraction dissipated by the cathode diminishing accordingly.

When the temperature of the water cooling the cathode is high with respect to the current, it is no longer permissible to regard q_K as constant but, on account of the exponential rise in the amount of vapour (cf. equation (9) and Fig. 3) with increasing cooling-water temperature, it has to be reduced more and more.

The temperature at the surface of the condensate, in analogy to equation (13), may be written as

$$T_F = T_W + \left(\sigma + \frac{s_{\text{Fe}}}{\lambda_{\text{Fe}}} + \frac{1}{\alpha_M} \right) q_c \frac{I}{A_c} \quad (14)$$

For the transfer from condensate to condensation wall, we may substitute $\sigma = 2^\circ\text{C}/\text{W}/\text{cm}^2$, according

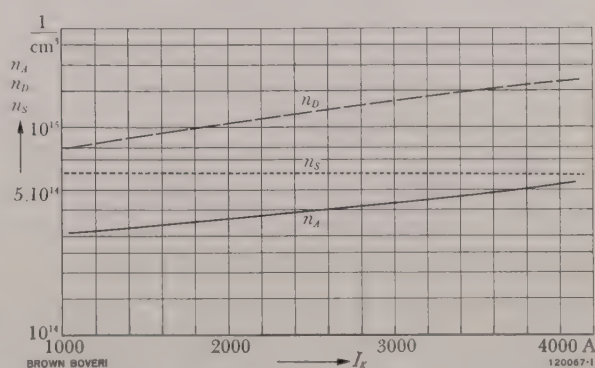


Fig. 4. — Curve of vapour density against load current in a water-cooled multi-anode mutator

At constant cooling-water temperature $t_W = 60^\circ\text{C}$

I_K = Cathode current

n_A = Vapour concentration in vicinity of anode

n_D = Vapour concentration in condensing space

n_s = Concentration of saturated vapour corresponding to temperature of cooling water

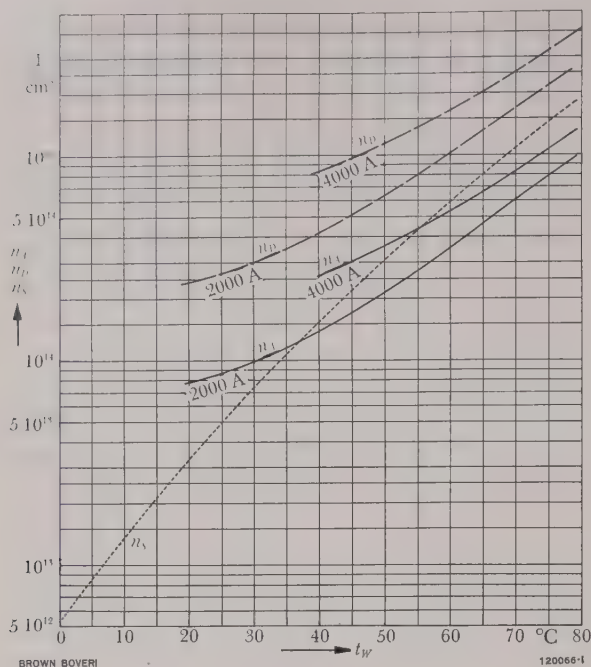


Fig. 5. — Curve of vapour density against temperature in a water-cooled multi-anode mutator with the current I_K as parameter

t_W = Temperature of cooling water [°C]
 I_K = Cathode current [A]
 n_A = Vapour concentration in vicinity of anode
 n_D = Vapour concentration in condensing space
 n_s = Concentration of saturated vapour corresponding to temperature of cooling water

to Risch [2]; for the losses dissipated by the condensation surface A_K we have to allow not only for the released heat of evaporation, but indeed almost the whole of the losses, provided they are not conducted away through the cathode water-cooling system. For a water-cooled tank, where the condensation surface can be assumed to be equal to the entire surface area of the jacket, this surface has to dissipate all the heat of recombination and the anode losses received by radiation.

Hence, if the small fraction of the losses q_A , which is dissipated by the anode plate, is taken into account, there remains a fraction q_c of the total arc voltage u_B , whose losses are transferred through the condensation surface, i.e.

$$q_c = u_B - q_K - q_A \quad (15)$$

In accordance with equation (12), and with the aid of (13), (14) and (15), Fig. 5 shows the distribution

of the vapour density in a water-cooled multi-anode mutator as a function of the cooling-water temperature, with the current as parameter. In Fig. 6 it is shown at constant water temperature as a function of the load current. In conformity with the standard practice, the density of the saturated vapour n_s corresponding to the temperature of the water is compared with the density n_A in the vicinity of the valve. Hence the vapour density in the tank n_D , as given by equation (12), has to be reduced by the anode superheating ratio $r = T_A/T_D$ to

$$n_A = n_D/r \quad (16)$$

According to Stefan-Boltzmann's formula the distribution of the anode temperature may be expressed to a close enough approximation by

$$T_A = T_{AN} \sqrt[4]{\frac{I}{I_N}} \quad (17)$$

Here, for the sake of simplicity, the anode losses are assumed to be proportional to the current and independent of the vapour density. Otherwise the fourth root of the anode loss ratio would have to be inserted in (17). As Fig. 5 shows, the curve of the vapour density in the valve is only slightly flatter than that of the saturated vapour. In the region used in practice for such tanks, values are therefore obtained at rated current, which do not differ very much from the density of the saturated vapour. Even at half the rated current the density of the vapour in the valve is only about 40 % below that of the saturated vapour.

Fig. 6 shows the relationship between the vapour density in the valve n_A and the cathode current. From the state at zero current (density of saturated vapour) to operation at rated current with full anode superheating, the vapour density in the valve does not rise. On the contrary, even at rated current it is still slightly below the density of saturated vapour corresponding to the cooling-water temperature. Without anode superheating the vapour density in the valve at rated current is about 2.8 times the no-load value, because in this case the density n_D is also prevailing in the region of the valve. From practical experience it is well known that high anode temperatures are desirable.

In order to compare the calculated value with detailed experimental results, the calculation was

performed for an old design of water-cooled multi-anode mutator of long-standing repute, large numbers of which are still rendering excellent service today. Measurements of the vapour temperature of this mutator were published by Risch [9]. These have been included in Fig. 7 (in particular, measuring point 2, because point 1 was obviously affected by the anode superheating), where they are compared with the vapour temperature T_D obtained from equations (12, 13, 14). The agreement may be regarded as satisfactory.

Vapour Density Distribution Inside the Jacket

In the new types of single-anode mutators for 100 and 300 A the discharge space is surrounded by a vapour jacket³ containing appropriate openings, as depicted schematically in Fig. 6. This has the effect of evening out the variation of the vapour pressure with temperature. On the one hand it raises the vapour pressure considerably at low temperatures because it does not allow the pressure to drop below a certain critical value determined by the quantity of vapour, so that an appreciable amount of the mercury spray evaporates inside the jacket. At the same time, by reducing the rate of flow of the vapour to the speed of sound, it diminishes the condensing effect of the wall temperature to such an extent that the vapour density inside the jacket is lower at elevated temperatures than it was in the former design of saturated vapour tank having no jacket.

From the generalized Bernoulli equation and from Poisson's equation for the adiabatic change of state, the emerging quantity of vapour [10, 14] is given by

$$G = A_0 \psi \sqrt{2 p_i \varrho_i} = A_0 \psi p_i \sqrt{\frac{2}{R T_i}} \tag{18}$$

in which ψ is a factor dependent solely on the pressure ratio p_0/p_i , expressed by

$$\psi = \left(\frac{p_0}{p_i}\right)^{\frac{1}{\kappa}} \sqrt{\frac{\kappa}{\kappa-1} \left[1 - \left(\frac{p_0}{p_i}\right)^{\frac{\kappa-1}{\kappa}}\right]} \tag{19}$$

³ When the word jacket is used, it means the actual metal screen inside the vessel, and not the space between it and the outer wall.

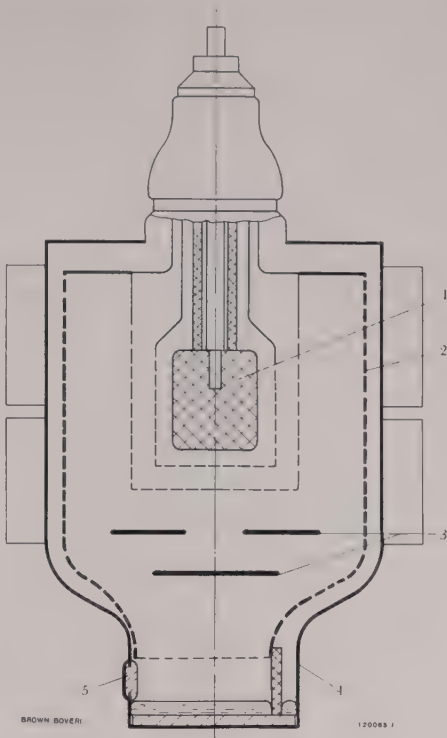


Fig. 6. – Single-anode mutator with vapour jacket

- 1 = Anode
- 2 = Vapour jacket
- 3 = Baffles
- 4 = Uninsulated cathode
- 5 = Insulated cathode

In the outlet cross-section of simple orifices the speed at the outlet cannot exceed a certain maximum value if the internal pressure is constant, no matter how much the external pressure is reduced. When the pressure ratio p_0/p_i is varied this critical value is given by the maximum outlet quantity according to equation (18), i.e. by ψ_{max} (cf. Fig. 8)

$$G_{max} = A_0 w_0^* \varrho_0^* = A_0 \psi_{max} \sqrt{2 p_i \varrho_i} = A_0 \psi_{max} p_i \sqrt{\frac{2}{R T_i}} \tag{20}$$

$$\psi_{max} = \left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}} \sqrt{\frac{\kappa}{\kappa+1}} = 0.512 \tag{21}$$

This maximum is attained at the sub-critical pressure ratio (see Fig. 8):

$$\frac{p_0}{p_i} < \frac{p_0^*}{p_i} = \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} = 0.487 \tag{22}$$

Corresponding to this there is a maximum outlet speed which, from (20), (21) and

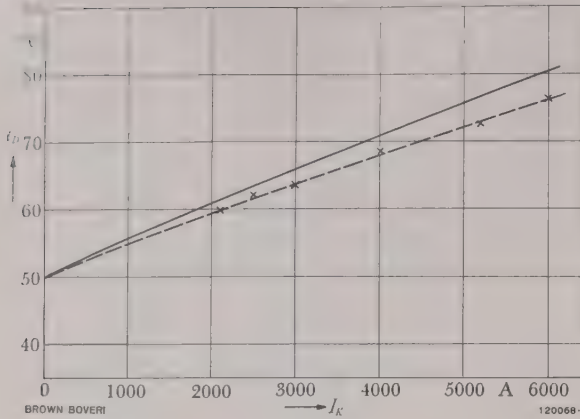


Fig. 7. - Curve of vapour temperature against load current in a water-cooled multi-anode mutator

At constant cooling-water temperature $t_W = 50^\circ \text{C}$

I_K = Cathode current

t_D = Vapour temperature in condensation space

× = Points measured by Risck [9]

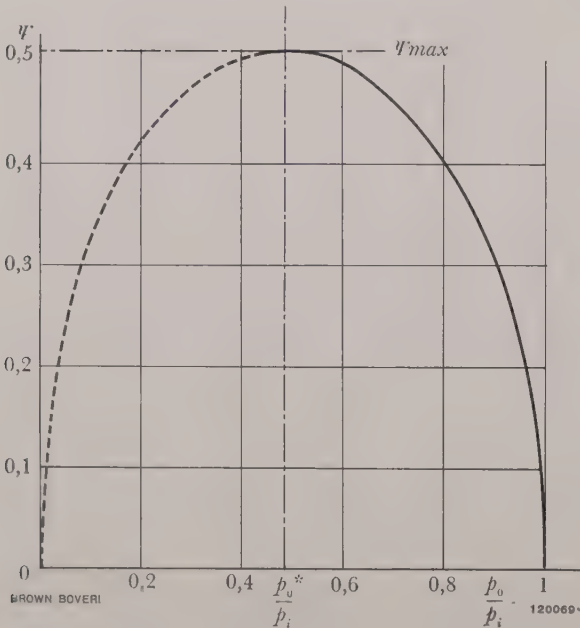


Fig. 8. - Function of flow from the mouth of the opening

$$\psi = \left(\frac{p_0}{p_i} \right)^{\frac{1}{\kappa}} \sqrt{\frac{\kappa}{\kappa-1} \left[1 - \left(\frac{p_0}{p_i} \right)^{\frac{\kappa-1}{\kappa}} \right]}$$

p_i = Pressure inside the vapour jacket

p_0 = Pressure at the mouth of the opening

p_0^* = Critical pressure at the mouth of the opening

$\kappa = c_p/c_v$ = Ratio of specific heats (for Hg vapour $\kappa = 5.3$)

$$p_i \left(\frac{1}{\rho_i} \right)^\kappa = p_0^* \left(\frac{1}{\rho_0^*} \right)^\kappa \quad (23)$$

works out to

$$\begin{aligned} W_0^* &\equiv c^* = \sqrt{\kappa \frac{p_0^*}{\rho_0^*}} = \sqrt{\kappa R T_0^*} = \sqrt{\frac{2\kappa}{\kappa+1} \frac{p_i}{\rho_i}} \\ &= \sqrt{2 \frac{\kappa}{\kappa+1} R T_i} \end{aligned} \quad (24)$$

From equations (22) and (23) we also obtain the critical density and temperature ratios

$$\frac{\rho_0^*}{\rho_i} = \left(\frac{2}{\kappa+1} \right)^{\frac{1}{\kappa-1}} = 0.65 \quad (25)$$

$$\frac{T_0^*}{T_i} = \frac{2}{\kappa+1} = \frac{3}{4} \quad (26)$$

With a super-critical pressure ratio p_0/p_i the outlet pressure p_0 is always equal to the external pressure p_D in the space between the jacket and the condensation surface and, in accordance with equation (22) (see also Fig. 8)

$$\frac{p_0}{p_i} = \frac{p_D}{p_i} < \frac{p_0^*}{p_i} = 0.487 \quad (27)$$

Thus the pressure inside the jacket is at the most twice as high as the external pressure p_D . For a slow rate of flow of vapour the latter is given by equation (12). When the rate of flow is of the order of the critical value, as given by equation (24), and thus of the thermal velocity according to equation (8),

$$\begin{aligned} W_0^* &= \sqrt{1.25 R T_i} = \sqrt{\frac{5}{3} R T_0^*} \\ w_m &= \sqrt{\frac{8}{\pi} R T_D} = 1.13 w_w \end{aligned} \quad (28)$$

allowance must be made for the fact that the Maxwellian speed distribution is disturbed and requires correction [11, 12, 13, 17].

For the super-critical range of pressure it must also be noted in practice that the outlet speed is greater than

$$W_0 = \sqrt{\frac{\kappa}{\kappa-1} \frac{p_i}{\rho_i} \left(1 - \frac{p_0}{p_i} \right)^{\frac{\kappa-1}{\kappa}}} \quad (28')$$

because this equation was derived by ignoring the high internal speed directed at the openings in the jacket. Then the square of this approach velocity has

to be added below the root sign [14, p. 267]. Thus this velocity is quite important.

When equation (12) is written with the appropriate correction value ξ and pressures are substituted for vapour densities, we obtain

$$\xi \frac{p_D}{\sqrt{T_D}} = \frac{1}{(1-\beta)} \sqrt{2 \pi \frac{k}{m_{Hg}}} \frac{1}{A_c} \left(FI + B n_K \sqrt{T_K} \right) + \frac{p_F}{T_F} \tag{29}$$

in which, for the critical velocity, ξ is approximately 3.4.

The effect of the strong vapour current directed at the condensation surface is such that, at quite a small difference between the temperatures of the vapour (t_D) and the condensate (t_F), the same amount of vapour can be made to condense as in the former type of tank without a jacket. A jet of vapour directed at the condensation surface simplifies condensation, as will be easily understood. Hence, at

high speeds, as in Fig. 9, it is possible that, despite the greater quantity of vapour, the vapour pressure is lower from a certain tank temperature than for a smaller amount of vapour and lower rate of flow. In practice, as may be seen in the point of intersection of the curves of the inverse anode current with and without jacket, this reduction outweighs the pressure rise due to the vapour jacket which, with supercritical flow can rise to a maximum of twice the external pressure. The somewhat higher superheating of the anode in the jacketed tank also contributes to this result, though its influence is small. As regards the manner in which the inverse anode current simulates the vapour density in the region of the valve, readers are referred to the comprehensive paper by Ludwig [15].

As was also taken into account in Fig. 9, the quantity of vapour increases by a multiple in the tank with jacket because a major proportion of the mercury spray can no longer reach the walls of the

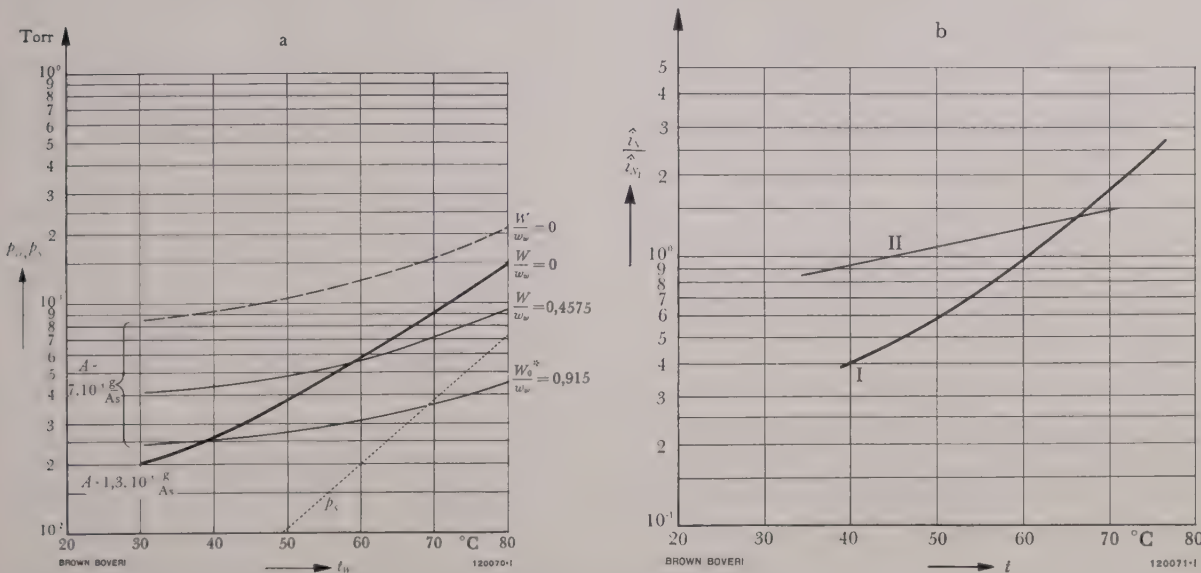


Fig. 9. - Curves of the vapour pressure (a) and peak inverse anode current (b) against temperature in a single-anode mutator with vapour jacket, continuously loaded with a mean value of 100 A

- a:
- t_w = Temperature of cooling water
 - p_D = Vapour pressure in condensing space
 - p_s = Saturated vapour pressure corresponding to cooling-water temperature
 - W = Velocity of vapour flow
 - $W_0^* = \sqrt{\frac{5}{3} R T_0^*}$ = Critical emergent velocity
 - $w_w = \sqrt{2 R T_D}$ = Most probable thermal molecular velocity with the Maxwellian distribution

- F = Quantity of vapour obtained per s from the cathode spot
- b: I = Single-anode mutator without vapour jacket
- II = Single-anode mutator with vapour jacket
- t = Temperature of mutator
- $\hat{i}_N$ = Peak anode follow current
- $\hat{i}_{N1}$ = Peak anode follow current of a mutator without vapour jacket at a temperature of $t = 60^\circ\text{C}$

tank directly, but is trapped by the jacket and evaporated there. On account of the increased rate of flow, this does not prove disadvantageous but, on the contrary, exerts a strong flattening influence on the curve of the vapour pressure in terms of the temperature. When the mutator is switched on cold, only a small amount of the mercury spray evaporates to begin with; but even then the pressure inside the jacket cannot drop below a limit imposed by the critical pressure, so that, in comparison with the tank having no jacket, it is more than twice as high and at heavy currents, i.e. for large quantities of vapour in accordance with equations (20) and (22), many times higher. At sub-critical pressures the outlet pressure is no longer equal to the external pressure, but adjusts itself to the quantity of vapour, maintaining a constant ratio $p_0^*/p_i = 0.487$.

Operation under such circumstances, with sub-critical pressure and, in consequence, with quite a large difference between the outlet and external pressures, only occurs when the tank is cold. For Fig. 9 it was assumed that the jacket is at its high steady-state temperature, corresponding to the mean current, and that the greater part of the mercury spray evaporates. The jacket absorbs most of the waste heat as heat of recombination and, since it is not in thermal contact with the cooled enclosure, can dissipate this heat by radiation at elevated temperature. At constant current according to equations (9) and (13), the quantity of vapour then increases less rapidly than the external pressure p_D on the jacket, with rising cooling-water temperature, owing to the large fraction dependent on the current, so that finally p_D reverts to the value of the outlet pressure p_0 and, as a result, super-critical pressure conditions, with $p_D = p_0$, are attained when the temperature continues to rise.

When studying the vapour densities in Fig. 9 it must be borne in mind that in the vicinity of the anode they are also reduced by the anode super-heating ratio and thus, as was shown in Fig. 5, lowered to the level of the curve for saturated vapour. For the fraction of the evaporation dependent on the current the figure of $F = 1.3$ mg/As was assumed for the tank with no jacket and thus with no contribution by mercury spray, while for the tank with jacket $F = 7$ mg/As was inserted, i.e. the greater part

of the 10.5 mg/As mercury spray determined by Issendorf [3], which, practically speaking, is rather high because in the apparatus employed for measurement that part of the mercury spray is also included which strikes the cathode surround and flows straight back into the cathode.

Cold-Starting and the Pressure Rise in the Tank with Jacket

Fig. 9 shows that, with the vapour jacket, considerable progress has been made towards the ideal of a vapour density independent of the temperature of the tank, which can be pre-determined by the design. Admittedly only the steady-state vapour conditions have been compared up to now. There still remains the rise in vapour density when the mutator is switched on cold, for which the theory cannot be explained in full in such an article. This must be reserved for a later date. But it will be demonstrated briefly that the improvement effected by the incorporation of a vapour jacket is at least equally as important as for steady-state vapour densities.

When a mutator of the classical type is switched on cold a marked improvement is only achieved when the tank warms up since the vapour density only rises very slightly with the current (see Fig. 4), even in the final steady state. At lower temperatures not even the final value of the vapour density for rated current is sufficient, and certainly no intermediate value during the rise in density. For this reason the rate of rise in the density is of no practical interest for such tanks. The final value itself has to be raised. The main increase in vapour density in such tanks thus accompanies the rise in tank temperature (Fig. 5). Hence, provided a rare-gas filling is dispensed with for the reasons to be given later, this means that it is necessary to preheat the tank electrically or by other means, with temperature regulation within narrow limits in operation, in order to be able to switch on an overload when cold and carry it continuously.

For the tank with a jacket, however, the tank temperature is not the deciding factor. Assuming the vapour is propagated at an infinite rate, the pressure increase in the jacket can be expressed, with the

aid of equation (20), by means of a simple differential equation, as follows:

$$\frac{d\varrho_i}{dt} + \frac{G_{max}}{V_H} - \frac{D}{V_H} = \frac{d\varrho_i}{dt} + \frac{A_0}{V_H} \psi_{max} \sqrt{2RT_i} \varrho_i - \frac{FI}{V_H} = 0 \tag{30}$$

In this equation the second term in equation (9) was neglected because, at low cathode temperatures, it is very much smaller than the other. Furthermore, for the quantity of vapour carried away the maximum value ψ_{max} was inserted, i.e. sub-critical pressure ratio. By means of this simplification the quantity of vapour passing through the jacket until critical pressure conditions are attained was deliberately made too high. This simply means that the emitted quantity of vapour is for a short time less than was assumed, while the pressure would in fact rise rather more rapidly. However, at heavy currents and low temperatures, i.e. low vapour densities, the critical ratio is rapidly attained, so that the above simplification is quite permissible.

The differential equation (30) yields the following rise time constant:

$$Z_t = \frac{V_H}{A_0} \frac{1}{\psi_{max} \sqrt{2RT_i}} = 2.3 \times 10^{-3} \frac{V_H}{A_0} \frac{1}{\sqrt{T_i}} \tag{31}$$

For the designs considered it is of the order of a few milliseconds. Any error in the figure assumed for T_i therefore has practically no effect, because once more it is the absolute temperature which is below the root sign.

The time constant mentioned above can only yield an approximate estimate, however, because it only takes into account the pressure rise in a single space, though in reality a number of spaces are involved (the space being divided by baffles and grids), connected in a kind of cascade, one after the other. This multiple effect problem can be dealt with mathematically. The simple differential equation (30) may be adopted as the asymptotic solution. In the derivation of the time constant the finite speed of propagation of the vapour was not taken into account either, though it is of the order of 10^4 cm/s and thus provides milliseconds which cannot be ignored with respect to the time constant. The speed of propagation of the vapour and the hindrance by

baffles and grids is roughly the same for both kinds of tanks, so that the conclusion is reached that their time constants are more or less equal. Indeed in both cases the peak arc voltage can be observed to decay at roughly the same rate at the point of arc starvation within the first few cycles. But in the jacketed tank the pressure increases by a multiple in this rise time because the final pressure at low temperature is many times higher than that in the tank without jacket, and therefore the point of arc starvation is considerably higher. The jacket must be warmer than the tank in order that the pressure may rise in this manner, and no condensation take place on the jacket. This is always the case in the event of idle periods lasting a few hours, since the jacket is not in thermal contact with the tank and can only give up its heat slowly as the temperature drops (the radiation diminishes as the fourth power of the temperature). For longer idle periods it is sufficient if the excitation is switched on a short time before—in conformity with the heat capacity of the jacket and the waste heat it absorbs—to bring the jacket up to the required temperature. It does not have to be specially stressed that the jacket can be heated up much more rapidly than the whole tank and with much smaller power (excitation current), as its heat capacity is more than one order of magnitude smaller and radiation only becomes detectable at quite a high temperature.

A rare-gas filling was deliberately dispensed with because its partial pressure is additional to that of the mercury vapour and, at the same operating temperature, noticeably reduces the anode blocking capacity and the electric strength. To fulfil equal requirements the operating temperature, which is tantamount to the load, would have had to be reduced. This effect is particularly marked in single-anode tanks in which, unlike in multi-anode tanks, the rare gas cannot be forced into the dome by a large amount of vapour. Furthermore, the risk of the rare gases being gettered under certain circumstances, the poorer conditions for condensation at high pressure, and finally a reduction in the useful life in the extreme cases, would have to be taken into account [16].

By means of the vapour jacket alone it has proved possible to attain an unprecedented overload capacity, and to retain it in the cold state. At the same

time this overload can be permitted, not only at low temperatures, but also at higher temperatures than previously and as continuous pulsating load with the rated current as mean value. Hence the working range has been considerably extended compared to condensation tanks.⁴ Moreover, to attain it there is no need to employ means of supervising and regulating the temperature.

The Vapour Jacket as Recombination Screen

In order to prevent the formation of a cathode spot, the vapour jacket must be insulated from the cathode, as shown in Fig. 4. Thus in tanks where the cathode is insulated from the body of the vessel, it may be directly bonded with the latter. If, however, the cathode is not insulated, the jacket has to be insulated from the body (see Fig. 6 right). Then it may be employed as a recombination screen at the same time and designed accordingly. As will be known, the task of the recombination screen is to cause the charge carriers to recombine before they reach the wall of the tank, so that the residual current at the wall is quite small in comparison with the excitation current, otherwise the stability of excitation might be endangered. The reduction of this current at the wall can be made to suit any requirements by suitable design of the screen. It is then no longer possible for the excitation current to suddenly break off. It is therefore permissible to dispense with restriking by an ignition rod, as in an ignitron, whose functions are very dependent on ageing (formation of deposit on the ignition rod), and are especially worsened by changes in the surface of the mercury pool. In the same manner it is possible to completely control the formation of an arc between the wall and the anode, parallel to the anode-cathode arc.

Improvements to Cooling and Layout

Apart from the high surge load capacity, the good cold-starting qualities without temperature regulation or heating, and the flexibility of the circuitry, as described in the foregoing chapters, the new tanks

equipped with vapour jacket rated 100 and 300 A also offer all the well-known advantages of single-anode tanks: inexpensive storage of spare tanks, lower arc voltage, permitting the adoption of the compact metalclad system,⁵ and low unit weight which, with the selected drawout design (see Fig. 10 and the coloured plate inside the front cover), allows the tanks and their auxiliaries to be assembled as separate "building blocks", facilitating rapid replacement. These advantages are considered to outweigh the drawbacks of the risk of the excitation breaking off, and the extra outlay for auxiliaries (excitation, ignition and ventilation). The preceding chapter explained how the risk of the excitation breaking off can be eliminated by radically reducing the wall current. Previously such interruptions were rare in single-anode tanks; when they did occur, however, they were attributed mainly to short circuits between the cathode and the body of the tank. By dispensing with the cathode insulation, the jacketed tank completely eliminates this cause of interrupted excitation. The disadvantage of the more extensive auxiliaries resulting from increasing the number of tanks, i.e. for ignition, excitation and ventilation, is balanced alone by the absence of any means of heating or measuring and regulating the temperature, so that the other advantages may be regarded as true progress.

In the third chapter of this article reference was made to the manner in which the maximum admissible operating temperature can be increased by incorporation of the vapour jacket. If the value of this temperature is given, the cooling system governs the temperature difference between it and the cooling air, needed to dissipate the heat generated

$$Q_N = \alpha_R \eta_R A_R \Delta t = \alpha_b A_M \Delta t \quad (32)$$

where

Δt = temperature difference between the cooled shell and the air temperature at the inlet

$\eta_R \Delta t$ = mean temperature difference between the surface of the cooling fins and the cooling air at the inlet

The better the cooling, i.e. the larger the product $\alpha_R \eta_R A_R = \alpha_b A_M$, the smaller the difference Δt

⁴ See Fig. 1 on p. 639.

⁵ See p. 645.

needed for the given amount of loss power, and the higher the maximum admissible temperature of the cooling air. Thus, by improving the cooling, it is possible to extend the permissible range of the cooling-air temperature still further upwards. Consequently the mutators of this type are provided with a new form of fins, which improves the heat transfer by 50 to 100 %. By employing fin material with a much higher thermal conductivity the temperature distribution over the length of the body can also be made more uniform. For the mutators rated 100 A the temperature difference Δt is now only about 10 °C. For the heat transfer coefficient, referred to the surface area of the cooling shell, it was possible to attain values of the order of 0.1 W/cm² °C, i.e. of the same order of magnitude as for water cooling (0.25 to 0.5 W/cm² °C). By means of this new fin design the permissible temperature for the cooling air has been increased so much that series cooling of two tanks is now feasible. In other words, the air may first pass through the lower row of mutators (see Fig. 3a on p. 647) and its temperature be raised accordingly (4 °C at full load), before it passes on through the upper row. This results in a very simple layout of the cooling system and, if requested, permits an air-to-water heat exchanger to be incorporated, so that a closed air circuit can be employed inside the cabinet. In this way the advantage of water cooling is achieved as it avoids the expense of installing air ducting, as well as eliminating the disadvantages, such as hydrogen diffusion, corrosion, difficulty of insulating the tank, especially with the anti-parallel connection, and the inability to replace a tank so easily.

By combining these new constructional elements, which have been subjected to exhaustive individual and endurance tests, with the old, well-tried elements, such as Kovar-glass seals for the anode, grid and excitation bushings, jet ignition, etc., Brown Boveri have succeeded in creating a very neat new design, whose performance, referred to the permissible surge power in MW which may be repeated as frequently as desired, gives figures of 320 kg/MW for the weight, 1.1 m³/MW for the volume, and 0.5 m²/MW for the floor area, permitting the new mutators to compete on level terms with modern uncontrolled silicon rectifiers. At the same time the performance with respect

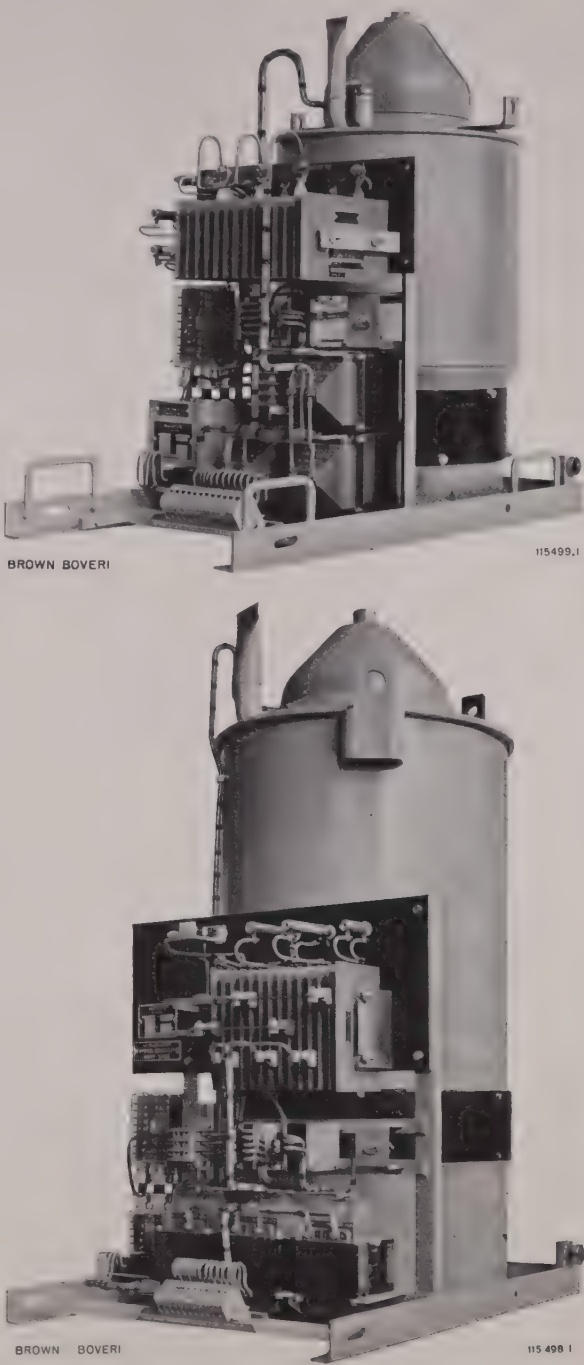


Fig. 10. – Single-anode mutators (with vapour jacket) types Lg 41 and Lg 61

Top:	Type Lg 41	Rated current	100 A
		Thermal limit	175 A
		Max. continuous inverse voltage	5 kV
Capable of withstanding load surges up to $4 \times I_n$			
Bottom:	Type Lg 61	Rated current	300 A
		Thermal limit	500 A
		Max. continuous inverse voltage	5 kV
Capable of withstanding load surges up to $3 \times I_n$			

to temperature was improved to such an extent that, for normal applications, there is no need for any supplementary equipment to maintain a definite temperature, and cooling can be carried out solely by an uncontrolled fan. Neither is there any need for supervision of the temperature.

(KME)

E. ANWANDER

Appendix

Meanings of the various symbols

A_0	Outlet cross-section of a simple orifice [cm ²]	p_s	Pressure of saturated vapour [Torr]
A_c	Condensation surface area [cm ²]	q_c	Fraction of energy lost over condensation surface [W/A]
A_K	Cathode area [cm ²]	q_K, q_A	Fractions of energy lost over surface of cathode and anode, respectively [W/A]
A_M	Surface area of mutator shell with cooling fins [cm ²]	Q_N	Mutator losses at rated current [W]
A_R	Surface area of cooling fins [cm ²]	R	4.22×10^5 [erg/°K.g] Gas constant of Hg vapour
B	Abbreviation defined by equation (7)	S	Total thermal resistance [°C/W/cm ²]
c^*	Critical speed of sound [cm/s]	s_{Fe}	Thickness of the steel walls [cm]
D	Quantity of vapour produced per second [g/s]	s_{Hg}	Thickness of the mercury layer [cm]
F	Quantity of vapour dependent on current [mg/As]	T_A	Anode temperature [°K]
G	Amount of vapour emitted by the jacket [g/s]	T_D	Temperature of the mercury vapour [°K]
I	Mutator current [A]	T_F	Temperature of the liquid (condensed Hg) [°K]
k	1.38×10^{-16} [erg/°K] Stefan-Boltzmann's constant	T_K	Temperature at the surface of the cathode mercury [°K]
m_{Hg}	328.2×10^{-24} [g] molecular weight of mercury	T_s	Temperature of saturated vapour [°K]
M_c	Quantity of condensate [g/cm ² s]	T_W	Temperature of cooling water
n_A	Vapour concentration in the vicinity of the anode [cm ⁻³]	Δt	Temperature difference between cooled shell and cooling air at inlet [°K]
n_D	Vapour concentration [cm ⁻³]	u_B	Arc voltage [V]
n_F	Concentration of saturated vapour at the temperature of the liquid (condensed mercury) [cm ⁻³]	V_G	Unoccupied volume of tank [cm ³]
$n_{i, 0}$	Vapour concentration inside the jacket, or at the mouth of the opening [cm ⁻³]	V_H	Unoccupied volume of jacket [cm ³]
n_K	Concentration of saturated vapour at the temperature of the surface of the cathode mercury [cm ⁻³]	W	Velocity of flow of mercury vapour [cm/s]
n_s	Concentration of saturated vapour [cm ⁻³]	W_0	Speed at which it emerges from the mouth of the opening [cm/s]
$p_{i, 0}$	Pressure inside the jacket, or at the mouth of the opening [dyn/cm ²]	w_m	Mean thermal velocity [cm/s]
		w_{mD}	Mean thermal velocity at the vapour temperature [cm/s]
		w_{mF}	Mean thermal velocity at the temperature of the liquid (condensed Hg) [cm/s]
		w_{ms}	Mean thermal velocity at the temperature of saturated vapour [cm/s]
		w_w	Most probable molecular velocity [cm/s]
		Z_c	Amount of condensate arriving [molecule/cm ² s]
		Z_D	Number of vapour molecules arriving [molec./cm ² s]
		Z_F	Number of molecules leaving the liquid Hg condensate [molecule/cm ² s]
		Z_t	Rise time constant of the density [s]

$\alpha_b = Q_N/A_M$	Heat transfer coefficient referred to cooled surface area of mutator shell [W/°K cm ²]
$\alpha_K, \alpha_M, \alpha_R$	Heat transfer coefficients at the cathode bottom, at the mutator shell and at the cooling fins, respectively [W/°K cm ²]
β	Reflection factor at the tank wall
β_K	Reflection factor at the cathode surface
η_R	Efficiency of the fins at full air speed, i.e. with heat transfer coefficient α_R
$\kappa = c_p/c_v = 5:3$	Ratio of the specific heats for Hg vapour
$\lambda_{Hg}, \lambda_{Fe}$	Thermal conductivity of mercury and steel [W/°K cm ²]
$\rho_{i, 0} = n_{i, 0} m_{Hg}$	Vapour density inside the jacket or at the mouth of the opening [g/cm ³]
$\tau = (1 - \beta)$	Transmission factor
*	Quantities marked with an asterisk refer to the critical state (rate of flow = speed of sound)

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PROPERTIES OF THE NEW BROWN BOVERI SINGLE-ANODE MERCURY-ARC CONVERTERS

621.314.65

Beginning by referring to the conditions to be fulfilled by mercury-arc converters in modern rolling mills, the present article describes the properties of the new range of Brown Boveri single-anode mutators rated 100 and 300 A, respectively. It is demonstrated that, owing to their being equipped with the "vapour jacket", these units are able to cope with the load surges occurring when operated with heavy reversing drives.

FOR MODERN reversing drives the time taken in reversal has to be as short as possible. Consequently increasing preference is being shown for static converters, particularly in cross or anti-parallel connection, as they exhibit the shortest dead times. The design and principle of these two-converter connections are described in a later article (see page 650). As it uses a simpler transformer, the anti-parallel connection is less expensive than the cross connection. Essential for the adoption of the anti-parallel connection is the availability of suitable single-anode converters, which have to possess the following properties.

High surge load capacity over a wide temperature range

High electric strength

Low backfiring rate, even at large delay angles

Design as excitron with excellent control properties and stable excitation to maintain the cathode spot under all circumstances likely to be experienced in operation

Design as pumpless, air-cooled tanks, assembled complete with all auxiliaries to form building blocks with a potential which can be freely selected

Accommodation of the building blocks in cabinets occupying a minimum of floor-space, with free choice of coolant

To satisfy these requirements Brown Boveri developed the single-anode converters rated 100 and 300 A, respectively. The units possess some remarkable new properties, which will now be discussed in detail.

Surge Load Capacity

With any two-converter connection, including the anti-parallel connection, the ratio of the surge load to the mean load current of the valves is very large because the converters are carrying the current alternately. For instance, it may be as much as 6 : 1 in an installation where the surge current is three times the rated figure. Single-anode converters with a high overload capacity therefore allow the favourable anti-parallel connection to be employed with heavy reversing drives of all kinds, without greatly exceeding the outlay for a single-converter connection.

Fig. 1 shows the overload capacity of the new single-anode units in comparison to that of the classical multi-anode rectifiers with and without rare-gas filling, as a function of the temperature of the tank. Whereas the multi-anode mutators, even at the optimum operating temperature, could only be overloaded with a current roughly corresponding to their thermal limit, the new units can cope with current surges amounting to four times the rated current in the case of the 100-A unit, and three times in the case of the 300-A unit. The difference in the surge load capacity becomes still more pronounced when the tanks are at room temperature (compare curve *a* in Fig. 1 with curve *d*).

The current-carrying capacity of mercury-arc converters is known to be limited by the arc voltage at temperatures below the optimum operating tempe-

perature; this voltage increases at such a rate at heavy current and decreasing temperature that undesirable secondary ignition may occur inside the tank, and possibly overvoltages. The reason for this is, in this case, that the ion density is insufficient to neutralize the negative space charge produced by the electrons. The density of the mercury vapour, which decreases exponentially with the wall temperature, is so small that not enough ions can be produced by the passage of current. In order to make the most of the load-carrying capacity of the multi-anode mutators, it was usual for them to be installed in specially air-conditioned rooms, or for them to be equipped with heating and temperature-regulating devices, in order to maintain the working temperature at the optimum level. For many years it has been common practice to include a certain amount of rare gas in pumpless mutators, so as to extend their temperature range downwards; at low temperatures the rare gas replaces the inadequate mercury vapour and allows the mutator to run at least at its rated current at such temperatures. It is well known that a rare gas filling lowers the electric strength and maximum admissible operating temperature of a mutator. If the filling were dimensioned to permit the passage of three to four times the rated current, the mutator would be useless for rolling mill service, owing to its poor electric strength. Investigations have also proved that, with a rare-gas filling, there is a risk of the gas reacting under certain circumstances, which may lead to loss of conductivity at low temperatures.

The new Brown Boveri single-anode converters have no rare-gas filling. The extraordinarily good conductivity of the cold unit was attained by incorporating a new constructional element, the vapour jacket (see page 629). During the passage of current the mercury vapour pressure inside the jacket is raised during the first cycle to such an extent that the currents shown in Fig. 1 can be carried. At higher temperatures the current-carrying capacity is limited by the increasing tendency to backfire, because the excessive number of mercury ions now present reduce the blocking capacity of the valve. Here too the vapour jacket exerts a beneficial influence. In contrast to the mutators without vapour jacket, the density of the vapour, and thus of the ions in the immediate vicinity of the valve, was actually less.

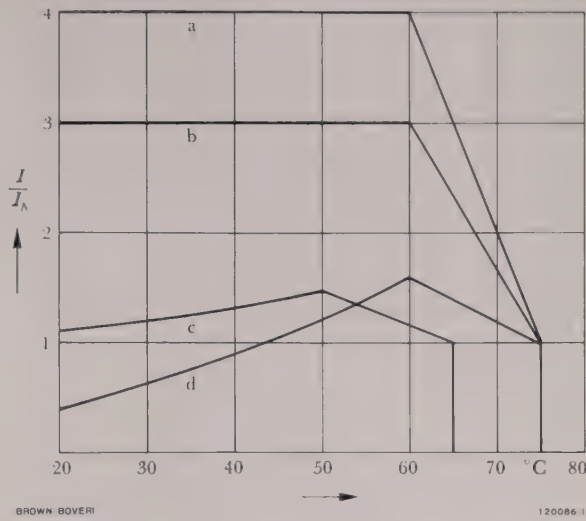


Fig. 1. — Surge load capacity I of single-anode mutators referred to the rated current I_N , at different temperatures

- a: Single-anode mutator type Lg 41
- b: Single-anode mutator type Lg 61
- c: Multi-anode mutator with rare-gas filling
- d: Multi-anode mutator without rare-gas filling

Thus at the lower end of the temperature range the jacket produces the desired rise in pressure needed to enable the converter to carry the current, and at

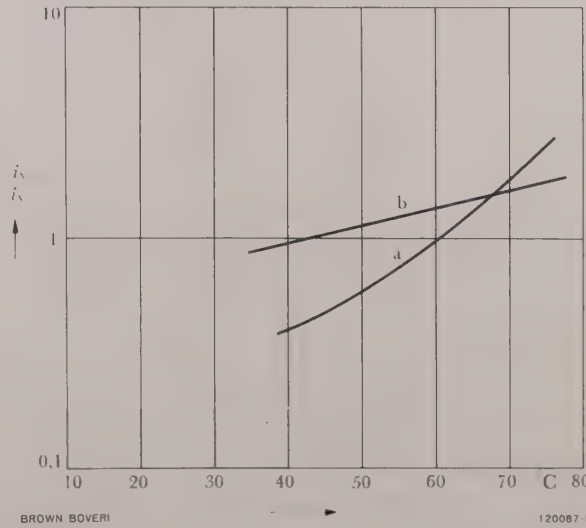


Fig. 2. — Peak post-arc anode current of a single-anode mutator with and without vapour jacket, in terms of the temperature

- a: Without vapour jacket
- b: With vapour jacket
- i_N = Peak post-arc anode current
- i_{N1} = Peak post-arc anode current of a mutator without vapour jacket, at a temperature of 60 °C

Electric Strength

The voltage stresses to which static converters are subjected by rolling-mill drives depend on the rated voltage of the motor being fed. The maximum armature voltage of such motors is in the region of 1500 V. The peak value of the anode inverse voltage corresponding to this d.c. voltage is at the most 3.5 kV with the most common hexapulse connections. The converter must be able to block this voltage dependably. As investigations have proved, there is no sharply defined limit for the electric strength of a mutator. The number of times it fails to block, like the backfire rate due to increased duty at the moment of extinction of the anode, is a probability function which, in terms of the inverse anode voltage can also be described by Poisson's formula

$$W_{(n)} = e^{-\mu} \frac{\mu^n}{n!}$$

in which μ is proportional to the inverse anode voltage $\hat{U}$. According to our measurements [3], the proportionally factor is 7×10^{-4} . Fig. 3 shows the measurements obtained with the single-anode converters investigated when subjected to surge loading. It will be observed that the probability of occurrence of a backfire in either of the two converters, whose design is similar, can be well expressed by the formula

$$W = \frac{e^{-7 \cdot 10^{-4} \hat{U}} (7 \cdot 10^{-4} \hat{U})^{22}}{22!}$$

One year's continuous operation by a group of six single-anode converters contains a total of roughly 10^{10} inverse periods at 50 c/s. From Fig. 3 it is evident that at the maximum inverse voltage of 3.5 kV, the probability of failure to block is very much less than 10^{-10} , i.e. much less than 1 failure per group of six per year in continuous operation. On account of the heavy surge currents experienced, a valve design with a particularly high electric strength is required for this.

The continuously admissible anode inverse voltage of 5.2 kV, derived from Fig. 3 for $W = 10^{-10}$, may occur temporarily as initial inverse voltage at the moment of extinction of the anode but not continuously. The anode blocking duty at the moment of extinction, according to [4], is governed not only by the initial inverse voltage Δu but also by the rate of change of

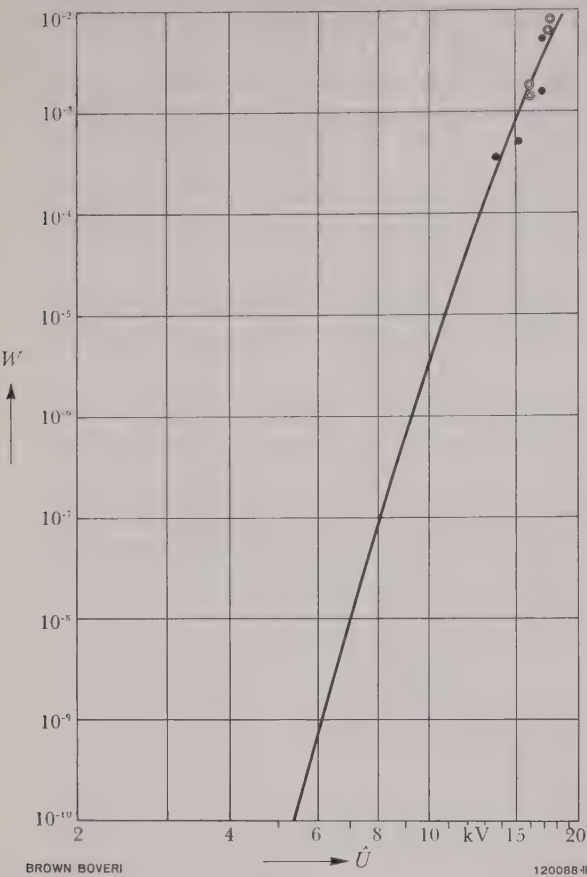


Fig. 3. — Probability of an anode failing to block, as a function of the peak anode inverse voltage $\hat{U}$ with surge loading

W = Probability
● = Mutator type Lg 61
⊙ = Mutator type Lg 41

$$W = \frac{e^{-7 \cdot 10^{-4} \hat{U}} (7 \cdot 10^{-4} \hat{U})^{22}}{22!}$$

the upper end of the range it reduces the vapour density, thereby appreciably widening the temperature range. This relationship is illustrated in Fig. 2, showing measurements of the post-arc anode current, which is representative of the mercury vapour density in the region of the valve; these figures are plotted against the mutator temperature. From the shape of the curve it is evident that with the vapour jacket it is possible to approach much nearer the ideal situation where the vapour density is not affected by the temperature of the tank. The physical relationships governing the variation of the vapour density in a tank with vapour jacket are discussed at some length in the preceding article (beginning on page 623).

the anode current di_a/dt . This relationship was taken into account during the determination of the characteristics dealt with in the next chapter, showing the load capacity in terms of the direct voltage and the delay angle.

Load Capacity in Terms of the Direct Voltage and the Delay Angle

For converters employed in conjunction with reversing drives the load capacity should, as far as possible, be independent of the degree of control $\cos \alpha$ (where α = delay angle). The anode blocking duty¹ of such converters must therefore be sufficiently high so that, even with conventional transformer impedance voltages, the probability of backfire¹ in the most unfavourable conditions ($\alpha = 90^\circ$) amounts to 10^{-10} , i.e. in 8700 hours operation not more than one backfire should occur per group of six anodes. Fig. 4 shows the load capacity of the new single-anode tanks in single-converter connection in terms of the direct voltage, with the degree of control as parameter. The currents shown are mean d.c. values per tank, the surge currents shown in Fig. 1 being permissible provided the mean value remains the same. These figures apply to normal transformer impedance voltages, referred to the permissible load current of the tanks as in Fig. 4.

For the anti-parallel connection it must be borne in mind that only half the number of installed single-anode tanks is in action at one time. The other half is either carrying the figure-eight current, or if this current is suppressed, these tanks are blocked altogether by the grid control. The alternation in the carriage of the current by the mutators takes place each time the direction of rotation is reversed. The anode blocking duty of the mutator which is momentarily carrying current is governed by the transformer, which is dimensioned for the full power of the installation. If the intention is to employ the anti-parallel connection, using the same number of tanks as for the single-converter connection, half the number of mutators must withstand the full transformer power during the passage of current. On account of the proportionality between the trans-

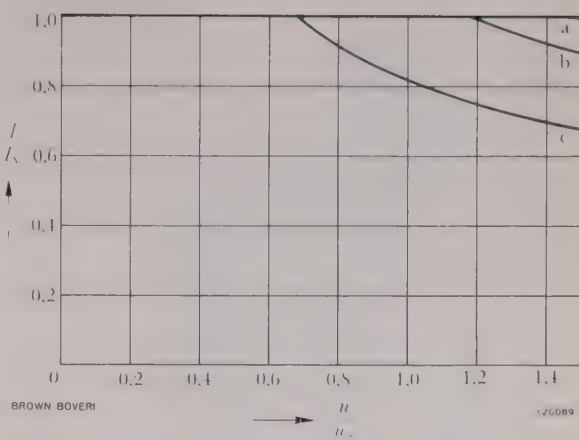


Fig. 4. – Load capacity of single-anode mutators type Lg 41 and Lg 61, in terms of the direct voltage and degree of control in single-converter connection

- I = Mean value of load current
 I_N = Rated current (mean value) for type Lg 41 100 A
for type Lg 61 300 A
- a: Delay, $\cos \alpha = 1.0$
b: Delay, $\cos \alpha = 0.8$
c: Delay, $\cos \alpha = 0$

former power and the anode blocking duty, the momentary value of the anode blocking duty is twice as high as with the single-converter connection. The arithmetic mean of the anode blocking duty and anode current, with respect to the full operating time, is equal, however, for both connections. The deciding factor in the planning stage is always the stipulation that the probability of backfire in an installation should not exceed a definite figure. For the relationship between the probability of backfire and the anode blocking duty the Poisson probability function may be replaced to a first approximation by the expression [3]

$$\frac{W}{W_1} = \left(\frac{B}{B_1} \right)^n$$

On account of the high power, e.g. $n = 6$, when the anode blocking duty is doubled, for instance, while maintaining constant mean value, the number of backfires occurring will not be the same, but $2^6/2 = 32$ times more than in the single-converter connection. Owing the operation being intermittent, the anode blocking duty to maintain constant rate of backfiring may only be increased by $\sqrt[6]{2}$, i.e., in the example, by $\sqrt[6]{2} = 1.08$ —in other words an increase of only

¹ As defined by Wasserrab [2].

8%. Reduction of the mean anode load current or increasing the impedance voltage of the transformer in order to lower the anode blocking duty is therefore inadmissible. Since in the Brown Boveri mutators the anode blocking duty increases with decreasing mean anode current, it is sufficient to reduce the current by one-third. But since the absolute value of the surge current must not be reduced, the surge load capacity referred to the reduced mean value increases from 4 to 6 for the type Lg 41 mutator rated 100 A, and from 3 to 4.5 for the type Lg 61 rated 300 A. As a result, with the anti-parallel connection and taking full advantage of the surge load capacity, the following surge currents can be permitted:

For installations with type Lg 41 units

$$3 \times \text{rated current}$$

For installations with type Lg 61 units

$$2.25 \times \text{rated current}$$

This conforms to practical requirements because for installations with high powers the ratio of the surge current to the rated current also becomes smaller.

The figures given for the loading were based on the results of exhaustive tests carried out at considerably higher anode blocking duties. Equivalent circuits were deliberately dispensed with to determine the anode blocking capacity, the mutators being operated in conjunction with transformers whose rated power greatly exceeded that of the mutator being tested, thereby increasing the duty. This is also important because one of the stipulations which must be fulfilled by a reliable converter is that it must be able to withstand repeated short-circuit loading at high transformer powers.

Stability of Excitation and Control Properties

The maintenance of the exciting cathode spot under all conditions likely to be encountered in service is a major problem for all single-anode converters with continuous excitation (Excitrons). If the excitation suddenly ceases, the cathode usually loses its emissivity immediately the main discharge is

extinguished, so that the affected tank does not carry any current during the time the excitation current is interrupted. The most frequent cause of interrupted excitation is the current in the excitation circuit, originating in the decaying residual plasma after the extinction of the main discharge and produced by the ions striking the cathode, the anode and the grid, and the electrons flowing away to the positive excitation anode. Since this current does not require any cathode spot, it forms a very effective shunt to the normal excitation current flowing through the exciting cathode spot. As a result of this shunt, the excitation current, determined by the exciter voltage and the resistance in the excitation circuit, splits up into the component flowing through the exciting cathode spot and the component produced by the residual ionization from the main discharge. The exciting cathode spot is extinguished when the current flowing through the spot drops below a certain minimum value. Therefore, to maintain the exciting cathode spot, the "shunt current" must always be less than the normal excitation current. Since the residual ionization at the moment of extinction of the main anode increases with the rate of change of the anode current di_a/dt , the tendency for the excitation to be interrupted also grows with increasing di_a/dt .

In modern single-anode converters, in which the cathode is not insulated from the tank, the shunt current increases by a multiple, by the addition of the "wall current" resulting from the addition of the wall surface to the cathode area. In consequence the stipulation that the excitation current must be greater than the shunt current can no longer be fulfilled with a reasonable outlay. By suitably designing the vapour jacket in the Brown Boveri converters it was possible to reduce the wall current by two to three orders of magnitude, so that the outlay for excitation does not exceed that for single-anode converters with insulated cathode. This appreciable reduction in the wall current is particularly necessary since the ions striking the wall during the conducting period can lead to an arc parallel to the main discharge, with its cathode spot on the wall of the tank. This spot may cease to burn at the start of the inverse period. But it is feasible for the spot on the pool of mercury to go out first, while that on the wall continues

burning. The outcome of this is that full main anode current flows via the wall during the succeeding period, leading eventually to damage or even destruction of the tank. From the results of systematic tests it proved possible to design the vapour jacket in such a way that interruption of the excitation, and migration of the exciting cathode spot to the wall due to the formation of a parallel arc can be avoided. There is no need to use igniter rods to restrike the cathode spot immediately the excitation ceases; these rods are affected by ageing in any case. To start the cathode spot from scratch, the principle of injection ignition is employed which has been used for years and is not affected by ageing.

The cathode spot constantly present on the mercury pool allows the main anode to strike precisely, provided the control grid and the deionization grid in front of it are expediently designed. When designing the valve of the new single-anode converters, in order to attain a low control power, special attention was devoted to ways and means of keeping the grid and anode firing voltages low and, as far as possible, independent of the operational state of the tank. Here too, the fact that the mercury vapour pressure is hardly affected by the wall temperature exerts a beneficial influence. The recovery time of the grid does not exceed the 15 elec. degrees usual at 50 c/s for heavy-current converters, even when subjected to the maximum surge load, thus ensuring that inverter operation without arc-through is possible.

The Building Block with Free Choice of Potential

In order to take full advantages of the well-known qualities of single-anode converters, such as the flexibility in the connection and the simpler storage of spare units, the individual mutator elements and their essential auxiliaries are combined to form a building block—or packaged unit—the potential of which can be freely chosen. A prerequisite for this is that the mutators are pumpless and air-cooled, and that the auxiliaries are reduced to the bare minimum.

For the successful batch production of pumpless mutators with a high overload capacity, it is necessary to resort to the aids of modern vacuum techno-

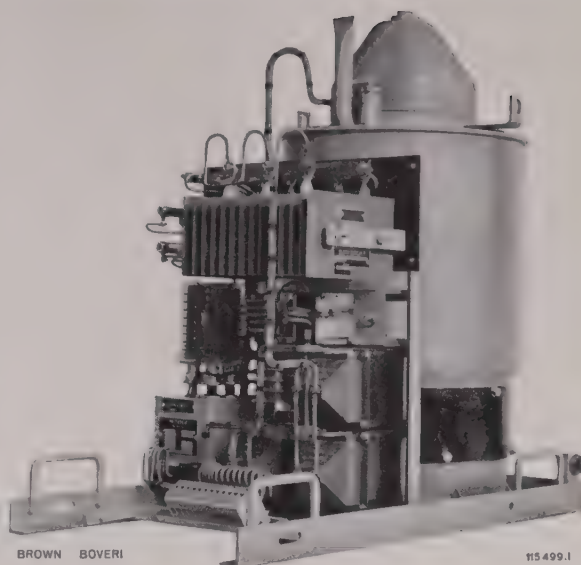


Fig. 5. — Packaged single-anode converter type Lg 41

Rated current $I_N = 100$ A

Surge current $4 \times I_N$

logy, the main stress being laid on gas-tight seals and degassing as far as possible. The methods adopted by Brown Boveri in this sphere have been described in detail in this journal [4]. A point worth mentioning is that, as the last phase in the extended process of evacuation of the single-anode mutators prior to sealing off, formation at 1.7 to 2 times the rated current is permissible with this robust design, so that evacuation, which plays a major role in determining the life of the tank, can be taken to a very advanced stage.

Air cooling was chosen because it eliminates the difficulties associated with water cooling, such as hydrogen diffusion and corrosion, as well as the long hoses needed to keep the potentials apart. By equipping the tanks with cooling fins, consisting of material having a high thermal conductivity, the temperature curve along the wall is almost as uniform as with water cooling; owing to the improved heat dissipation the temperature rise of the tank is some 50 % less than that obtained with normal steel fins.

Owing to the insensitivity to temperature, there is no need for any expensive system of fan control. The auxiliaries contain the very bare minimum of equipment, such as a fan, the ignition and excitation circuits with supervision, the source of the grid bias

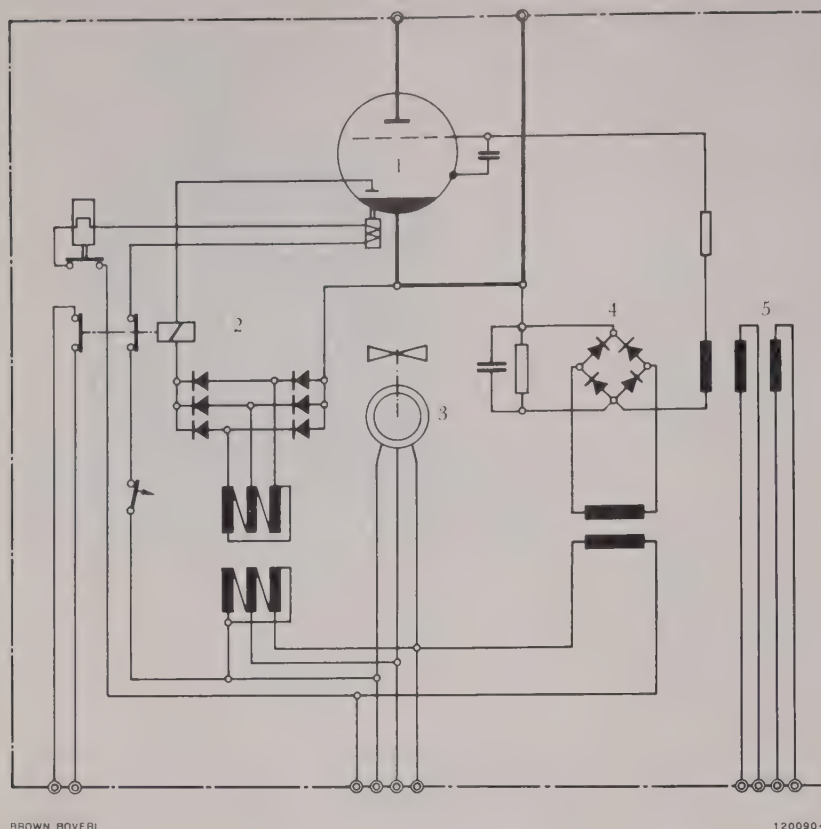


Fig. 6. — Circuit diagram of a packaged single-anode mutator type Lg 41 for metalclad enclosure

- 1 = Converter
- 2 = Ignition and excitation
- 3 = Fan
- 4 = Source of negative grid bias
- 5 = Pulse transformer for control grid

and pulse transformers for the control grid. Fig. 5 shows a complete building block with a packaged unit type Lg 41, the circuit diagram of which can be seen in Fig. 6.

The accommodation of these easily interchangeable units in suitable cabinets, as well as their layout and ventilation are described in the next article, beginning on page 645.

The single-anode converters described above are ideal for use in those situations where their outstanding properties can be fully utilized, namely their high surge load capacity, their insensitivity to change of temperature, the easy storage of spares and the packaged design. For rolling-mill drives involving only slight overloads, the multi-anode mutators will continue to be employed, as the open-type

installation and the lower outlay for auxiliaries (only 1 fan and 1 exciter set for 6 anodes) frequently allows a lower price per kilowatt to be attained.

(KME)

K. ROTH

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THE NEW METALCLAD TYPE OF SINGLE-ANODE
MERCURY-ARC CONVERTERS

621.314.65

The construction of single-anode mercury-arc converters (mutators) as integral, interchangeable units complete with all their auxiliaries, for installation in metaclad cabinets, offers various advantages when planning converter installations. The most important operating properties of these converters are briefly described, followed by details of possible methods of installation, methods of cooling and the design of the cabinets.

IN ADDITION to their well established range of multi-anode mercury-arc converters, Brown Boveri now possess a range of new single-anode units. The graduation of their ratings was made such that the most economical units can be employed for every application. These single-anode tanks are pumpless, air-cooled mercury-arc converters with control grids,

their conception and design being based on many years' experience gained by Brown Boveri in the manufacture of static converters, combined with the results of the latest research and development.¹

Fig. 1 illustrates the new range of single-anode mutators, which are shown as packaged units complete with their auxiliaries; the table below lists the main data of the various units. The auxiliaries are insulated for the full service voltage with respect to the mutator, so that any kind of converter connection can be obtained by combining the requisite number of packaged units, or "building blocks", of the same kind.

The values of current shown in the Table are mean d.c. values applying at an arcing time of 120 electrical degrees. The high overload capacity, charac-

¹ See article beginning on page 623.

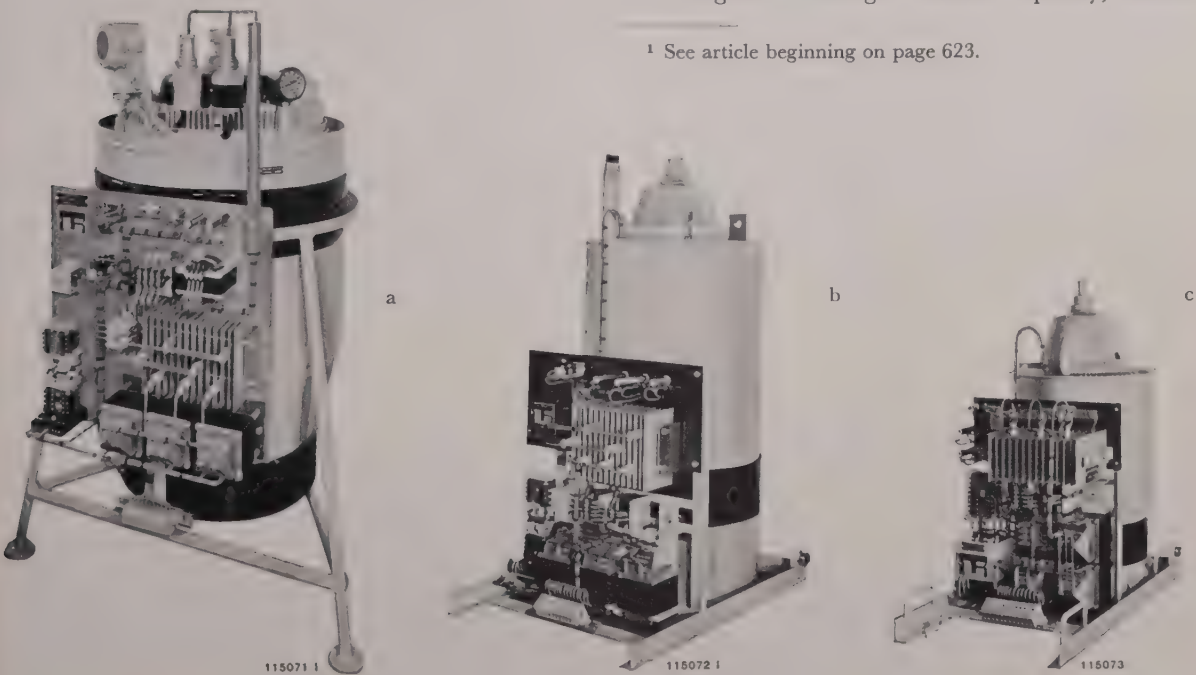


Fig. 1. — Single-anode mutators, packaged units complete with auxiliaries

- a: Type Lg 91 with auxiliaries, mounted on chassis
- b: Type Lg 61 with auxiliaries, packaged drawout unit
- c: Type Lg 41 with auxiliaries, packaged drawout unit

teristic for the single-anode tanks, is largely independent of the degree of control, which is a sure indication of their ideal suitability for use with reversing industrial drives.

As a result of the completely new constructional design of the single-anode tanks, heavy load surges can be withstood when the tank is warm or cold, without any need for a rare gas filling or special equipment for regulation of the temperature.²

The units type Lg 41 and 61 have an uninsulated cathode and vapour jacket. The latter, on the one hand, prevents the wall from being subjected to a stream of mercury ions and, on the other, renders the vapour pressure largely independent of the tank temperature and thus allows the mutator to operate in a far wider temperature range than was previously possible. The mutator type Lg 91 is of the conventional design with insulated cathode.

The principle guiding the design of the cabinets was the stipulation that, as regards erection and ventilation, they should conform to modern installation practice. The metalclad design was adopted (this term being in analogy to the method of installing switchgear) because the cabinets can then be combined with those containing switchgear and control gear, as well as auxiliaries of all kinds. Consequently the main dimensions of the mutator cabinets conform to those that have been standardized for switchgear.

The assembly in cabinets allows a very flexible arrangement to be employed in the installation, regardless of the presence of other elements. All

² See article beginning on page 634.

Mutator type		Lg 41	Lg 61	Lg 91
Rated current	A	100	300	600
Thermal limit current*	A	175	500	900
Max. permissible surge current (short-time)	A	400 $= 4 \times I_n$	900 $= 3 \times I_n$	1200 $= 2 \times I_n$
Max. sustained inverse voltage	kV	5	5	7.5
Method of installation		Cabinet with 6 units	Cabinet with 3 units	Cabinet with 3 units
Cabinet dimensions (width × height × depth) m		1.3 × 2.2 × 0.8	2.0 × 2.2 × 0.9	2.7 × 2.2 × 1.2

*Maximum current for which the tank is thermally dimensioned.

components are accessible from the front. A few typical arrangements are illustrated in Fig. 2. Whereas the layouts in Fig. 2a and c are specially suited to large installations where the mutators are housed in separate rooms, the layout in Fig. 2b or d may be chosen for a smaller installation, such as for the drive of a machine tool or mines winder. The recessed mounting (d), in particular, is most economical as regards space.

When planning mutator installations special attention always has to be devoted to the ventilation of the mutators and the rooms in which they may be installed. There are various reasons for this. Firstly the heat generated by the tanks has to be

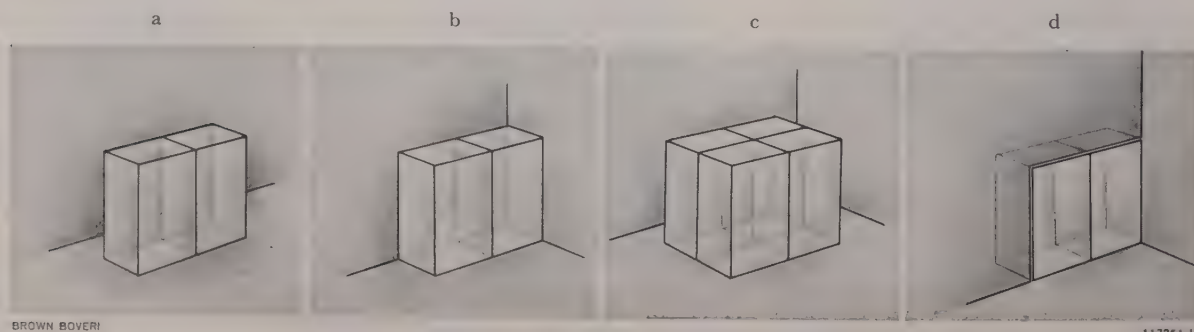


Fig. 2. — Alternative arrangements of cabinets containing single-anode packaged mutators

a: Floor mounting, single row

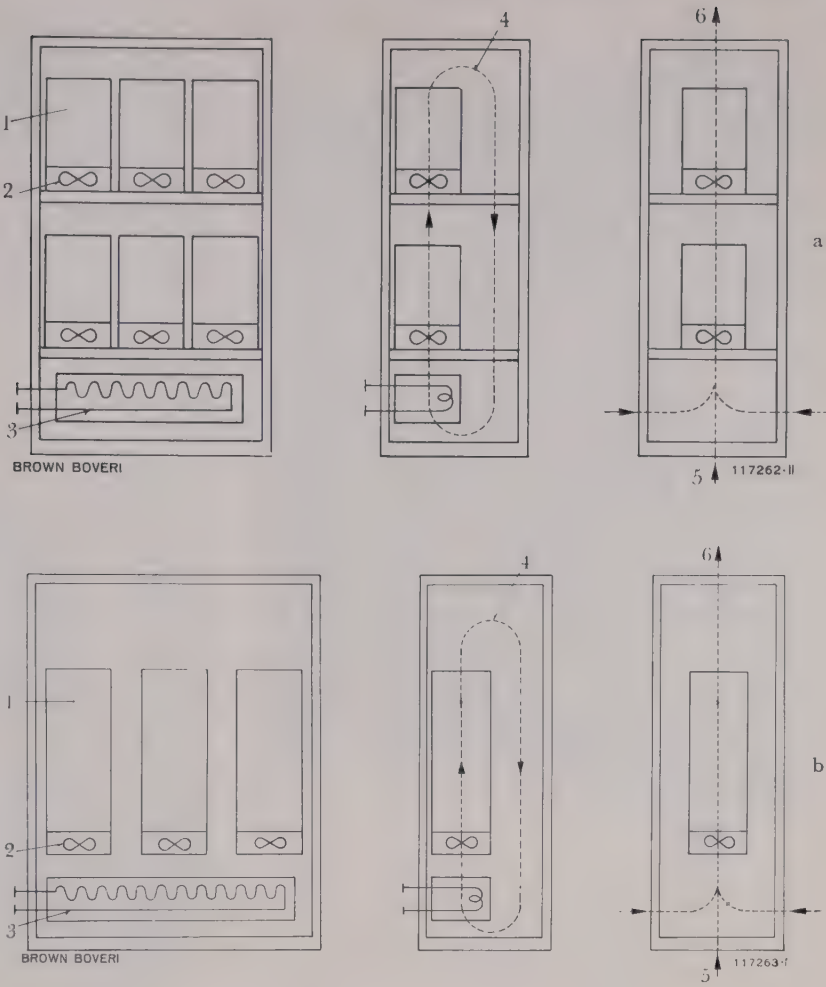
b: Wall mounting

c: Floor mounting, double row

d: Recessed mounting

Fig. 3. - Methods of ventilating mutator cabinets

- a: Ventilation of cabinets containing mutators type Lg 41
- b: Ventilation of cabinets containing mutators type Lg 61 or 91
- 1 = Single-anode mutators
- 2 = Fans
- 3 = Air-water heat exchanger
- 4 = Air flow with closed circuit
- 5 = Air intake with open circuit (from front, back or below, as desired)
- 6 = Air outlet with open circuit



dissipated; then, those mutators having an insulated cathode of the conventional design require a controlled amount of air in order to maintain the optimum operating temperature of the tank. Mutators of the new design with vapour jacket do not require any equipment to supervise or regulate the temperature; their fans are always running at full speed. These tanks are always ready for immediate operation at any ambient temperature.

The various methods of ventilating the cabinets are illustrated in Fig. 3. In principle, one may choose between the following methods:

- Cooling air drawn in from the room through openings in the back or front of the cabinet.
- Cooling air drawn in from the basement or through a duct from a fresh air supply.
- Closed-circuit cooling in a hermetically sealed cabinet equipped with a air-water heat exchanger.

All variants of the same type of mutator have the same kind of chassis for mounting in the cabinet. They only differ from one another in the enclosure and the possible inclusion of a heat exchanger. They permit almost any combination with the room ventilation, for example:

- Free exhaust without any heat exchangers, when installed in a room providing an adequately large volume of circulated cooling air.
- Installation without causing a draught in the room by incorporating a heat exchanger in the cabinet; if the volume of the room is limited, this method saves space due to the ability to dispense with ducting.
- Cooling circuits with extra fans and separate heat exchangers, the air being carried by special ducts under the floor, or with exhaust into the room direct.

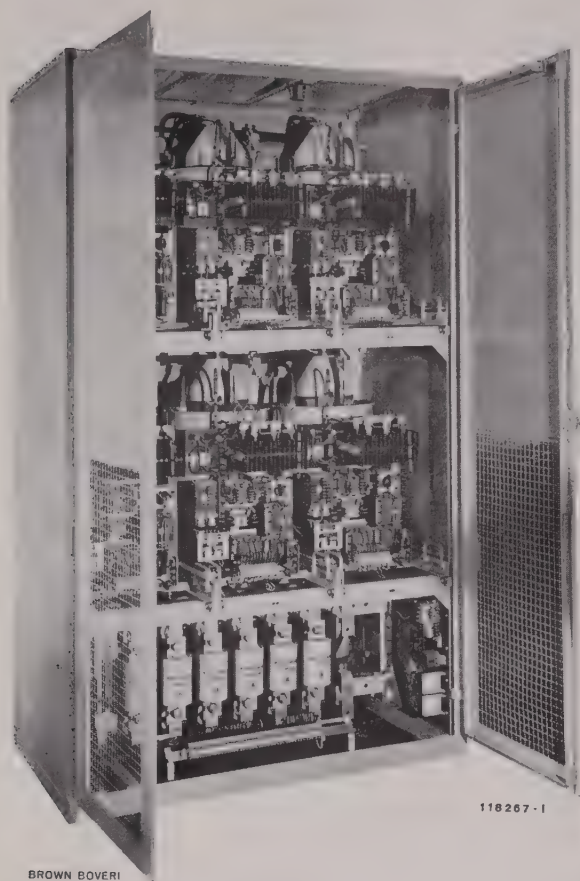


Fig. 4. – Cabinet containing six units type Lg 41

Data of each unit:

Rated current	100 A
Peak current	400 A
Max. direct voltage	1500 V

Fig. 4 shows a cabinet containing six units type Lg 41. These units are arranged in two rows of three. Fig. 5 shows the same cabinet with its doors closed, in which the air inlet openings are clearly visible. The rate of flow of the air at the inlet is less than 1 m/s. With the mutator units removed, the cabinet can be transported by four carrying loops, which are later removed. The auxiliaries are fed separately for each row, thus allowing two quite distinct drives, each requiring three tanks, to be operated from a single cabinet. The six anode fuses and their supervisory elements belong to the standard equipment. In the event of a fuse blowing, the defective unit can be found by inspecting the indicators on the fuses themselves. The fuses are, of course, installed in an easily accessible position. To protect the operating

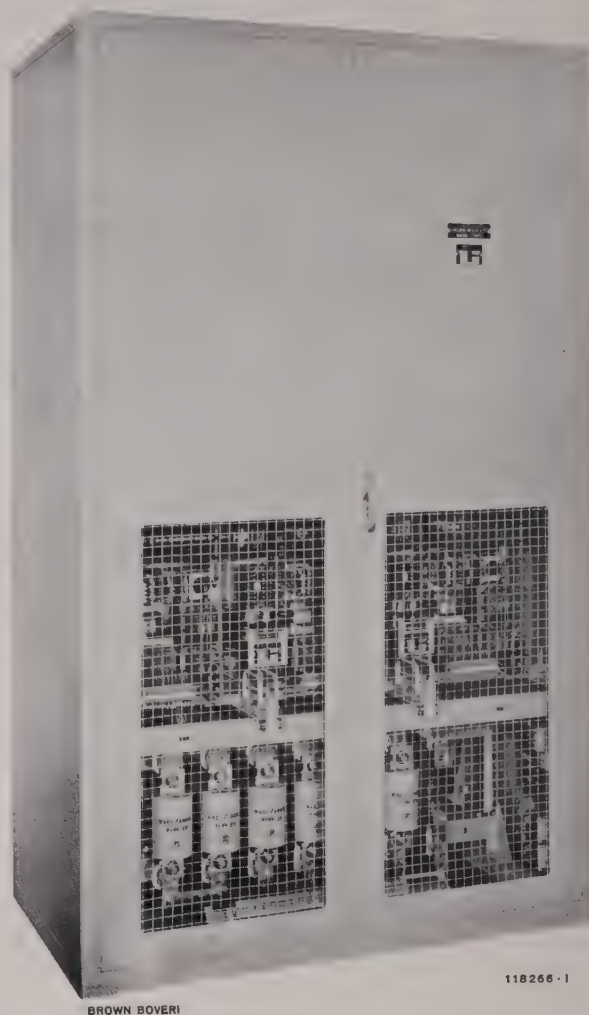


Fig. 5. – Cabinet containing six units type Lg 41 with air intake through the closed doors

Dimensions:

Width 1.3 m	Height 2.2 m	Depth 0.8 m
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staff, a door contact automatically disconnects the installation when the door is opened, thus enabling work to be carried out inside the cabinet in complete safety. In addition to the air-water heat exchanger, other optional items are anode current transformers for use with protective and measuring equipment.

Having regard to the high r.m.s. values of the anode currents (up to 350 A for the type Lg 41), screw connections are provided for the main terminals. Robust screwed terminals are employed for all auxiliary leads.

The drawout units are ventilated in pairs in series from the bottom upwards, i.e. the air, after cooling

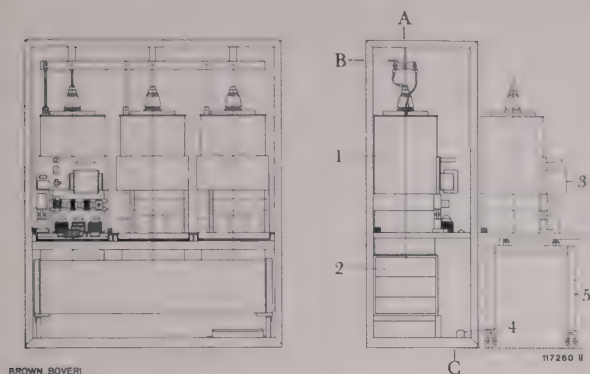


Fig. 6. — Cabinet for three units type Lg 61 or 91

The cabinet can accommodate three drawout units. On account of their greater weight, a transport trolley is provided.

1 = Drawout single-anode mutator with auxiliaries

2 = Air-water heat exchanger (optional)

3 = Mutator auxiliaries

4 = Terminals for auxiliary wiring

5 = Trolley for transport

A, B, C = Facilities for running the anode and cathode leads

the lower tank, passes on to the upper tank and cools it before being expelled. This is made possible by the high efficiency of the cooling fins and by the fact that

operation of the mutator is largely independent of its temperature. Hence the amount of air circulated is halved, thereby reducing the size of the ducting and the dimensions of the heat exchanger, if provided.

Fig. 6 shows the arrangement of the cabinets for mutators type Lg 61 and 91. In this case each cabinet only contains three units. Alternative facilities are provided for the connection of the heavier main leads, in contrast to the cabinet for type Lg 41, in which the main leads are always brought in from below. For transport and replacement of the units a trolley is provided, whereas the lighter type Lg 41 can be carried by the four handles provided (see Fig. 1).

To the advantages of the single-anode mutator mentioned at the beginning of this article may be added their suitability for installation in metalclad cabinets. The flexibility of installation, combined with the various possible methods of ventilation, provide a wide choice for the planner, who can exploit them to obtain the most expedient and harmonious arrangement for the complete installation.

(KME)

P. SCHNEIDER

TWO-CONVERTER CONNECTIONS WITH SUPPRESSED FIGURE-EIGHT CURRENT

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The logic elements of the Brown Boveri electronic system can be combined with analogue closed-loop control systems. A typical application is described in this article, which explains the nature and advantages of two-converter connections in which the figure-eight current is suppressed, and the principle of a simple current control system. The second part of the article is devoted to a number of practical applications for armature and field supply. A system of speed control with cascaded current control is described as an example of armature supply. Contiflux and Ward-Leonard generator field control are examples of the latter form of supply. Finally a system of discontinuous field supply as employed for reversing drives with field reversal is dealt with.

Nature and Advantages of Two-Converter Connections with Suppressed Figure-Eight Current

IN REVERSING d.c. drives, where the motor field is constant, the armature current has to change direction when the flow of energy has to be reversed. A feature of the Ward-Leonard drive is the easy reversal of the current. It is enough to change the sign of the difference between the e.m.f. of the generator and the motor to make the current flow in the other direction. In a drive fed from a static converter the current immediately becomes zero when the e.m.f. of the motor is raised above that of the converter. The voltage of the converter can be reversed, but not its current. In order to benefit from the well-known advantages of static converters with reversing drives, it is necessary to employ separate rectifiers for each direction of the current. Instead of feeding the armature of a motor, the two converters can feed a load of more variable nature, such as a motor field.

The two converters can be connected together in two quite distinct ways. One is the cross connection illustrated in Fig. 1a, in which the converters are either connected to two separate secondary windings of one transformer, or to two different transformers.

The cathodes are inter-connected through the load, and the two main circuits are closed by the cross-connections between the cathode and the neutral of the opposite system. In this arrangement the cathodes of the rectifier sections of the two systems are common, so that it is also possible to use multi-anode mercury-arc converters.

Fig. 1b shows the anti-parallel system. Connected to each phase of the transformer are two static converters, working in opposite directions, so that the cathode of the one is joined to the anode of the other. On the load side all the cathodes are connected in parallel for the one direction of the current, while for the other all the anodes are paralleled. This arrangement therefore requires single-anode converters. The advantage of the anti-parallel connection over the cross connection is that the transformer only has to have one secondary winding.

For drives employing semiconductor thyristors, on the other hand, the anti-parallel bridge connection (as shown in Fig. 2) is particularly interesting. The path of the current at any moment is closed through two converters at the same time, and does not lead back to the neutral of the transformer but to another phase. The advantage of this arrangement is that the ratio of the peak value to the mean value of the current in a rectifier is reduced; simultaneously the ratio of the maximum inverse voltage to the maximum direct voltage is also more favourable. It is well known that the maximum inverse voltage of semiconductor rectifiers is smaller than that of mercury-arc rectifiers. For this reason this circuit allows better use to be made of the thyristors. A bridge arrangement of this kind, equipped with the new Brown Boveri silicon thyristors type CS 100, can handle an output of about 65 kW.

For the control system it is immaterial whether the converters are in cross connection or anti-

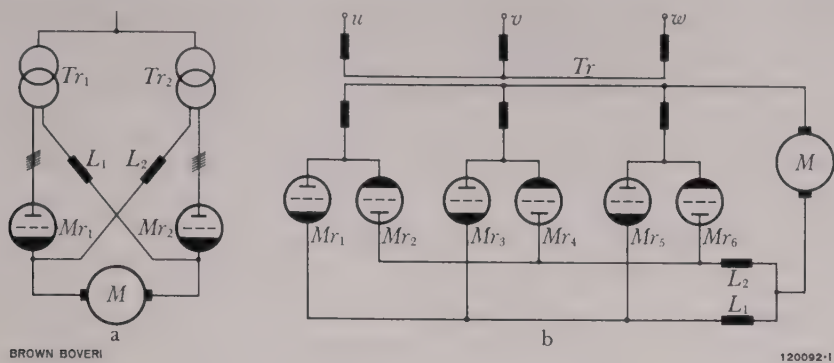


Fig. 1. - Two-converter connections

a: Cross connection

- Tr_1, Tr_2 = Transformers
- Mr_1, Mr_2 = Mutators (mercury-arc converters)
- M = D.C. motor
- L_1, L_2 = Reactors limiting the figure-eight current

If the figure-eight current is suppressed, the reactors L_1 and L_2 can be dispensed with.

b: Anti-parallel connection

- Tr = Transformer
- Mr_1, Mr_3, Mr_5 = Mutators for the first direction
- Mr_2, Mr_4, Mr_6 = Mutators for the second direction
- M = D.C. motor
- L_1, L_2 = Reactors limiting the figure-eight current

If the figure-eight current is suppressed, the reactors L_1 and L_2 can be dispensed with, as in the cross connection.

parallel. Therefore, if the two systems are considered as parts of a closed control loop, they may both be referred to jointly under the common term of two-converter connection.

Hitherto the usual method of controlling two-converter arrangements was for the two converters to be controlled simultaneously in opposite senses. The one is acting as a rectifier, giving power up to the load. For the other the input voltage is negative; it therefore acts as an inverter and is controlled to the same voltage. The mean values of the two converter voltages are kept equal; their momentary values, however, are different. This produces a current which flows round through the entire system and, with special allusion to the cross connection, is referred to as the "figure-eight" current. Unless special precautions are taken, this current can attain quite high values. It must consequently be limited to a tolerable level by including reactors in the two converter circuits. These reactors are very expensive items, especially in large installations. When high powers are involved, it may also be necessary to include a special control system for the figure-eight current, which influences the grid control of the two converters in such a manner that the figure-eight current is constantly kept down to about 10% of the rated current. Finally, the figure-eight current acts as a constant impedance for the mains.

A new solution was arrived at during the development of the digital elements of the Brown Boveri electronic system. By means of a contactless relay circuit, referred to simply as a logic element, it is possible to ensure that only one converter carries current at a time, thus suppressing the figure-eight current altogether. When the current is reversed, the change from one converter to the other is effected in a brief dead-time of 6–10 ms.

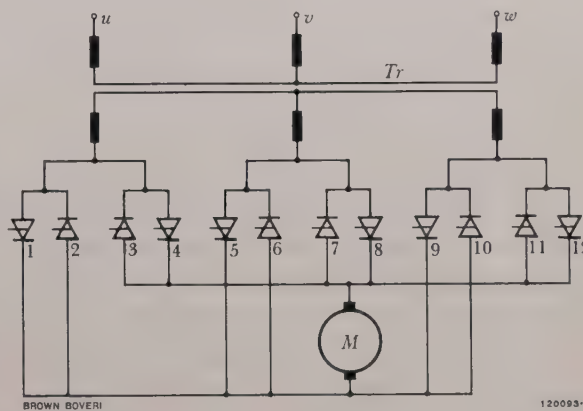


Fig. 2. - Anti-parallel bridge circuit with semiconductor rectifiers

- Tr = Transformer
- M = Motor
- 1, 3, 5, 7, 9, 11 = Rectifiers for the first direction
- 2, 4, 6, 8, 10, 12 = Rectifiers for the second direction

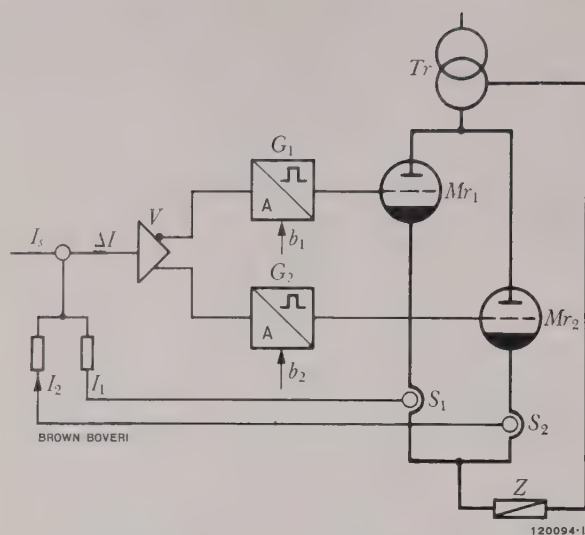


Fig. 3. — Current control circuit for anti-parallel connection with suppressed figure-eight current

- Tr = Transformer
 Mr_1, Mr_2 = Converters
 S_1, S_2 = Current transformers
 Z = Load, e.g. motor
 G_1, G_2 = Grid control sets
 V = Control amplifier
 I_s = Desired value for current
 I_1, I_2 = Actual values of current
 I = Deviation
 b_1, b_2 = Blocking signals for grid control sets

Principle of a Simple Current Control System

The basic principles of a two-converter connection in which the figure-eight current is suppressed will now be considered. Reference is made to a current control system, such as the one shown in Fig. 3, in which Z may be any load, for example a motor. This circuit may form part of a speed control system in the case of armature feed, or voltage control when the field is fed. The desired value of the current is assumed to vary continuously as a function of some other external variable. The actual value of the current is given by the two separate currents, at different polarities, corresponding to the directions of the desired value. This solution was chosen in order that a figure-eight current can be correctly determined if it occurs. If, for any reason, both converters should carry current at the same time, both grid control sets would immediately be blocked by

the logic element. Thus a figure-eight current is suppressed in any case.

The two grid control sets are controlled by an equal and opposite amount by the push-pull outputs of the control amplifier. If the two converters were both in operation at the same time, they would both produce the same mean voltage, though the one would be acting as rectifier and the other as inverter. The circuit is largely identical with a two-converter connection with smoothing reactor but without control of the figure-eight current, as was usual hitherto. Each grid control set can also be influenced by a logic signal (b_1 and b_2). If the grid control is to function normally, the logic signal must have the value 0; if it is 1, the grid control set concerned does not emit any pulse to the respective converter, so that the latter cannot carry current.

In the current control system under consideration, the converter 1, for instance, is in operation and allows the current I_1 to flow. In this case the desired value is positive. If in this initial state a negative desired value is given, the control system reduces the current I_1 to zero, the logic element detects this disappearance of the current and blocks the first grid control set. After a brief time-lag the second is released, allowing the valve which was previously carrying current to attain its full blocking capacity. The control system then supervises the build-up of the current I_2 to the preset value. The change back to the original direction is effected accordingly.

The stipulation that the switching actions must be performed rapidly and accurately leads to contactless elements of the kind belonging to the Brown Boveri electronic system. The following tables list the most important elements of logic circuits. Table I shows AND, OR and NOR operators. The standardized components of the Brown Boveri electronic system have three or four inputs; the diagrams in Table I must therefore be extended accordingly. An AND operator may be replaced by a NOR operator, when the following identity has been established.

$$e_1 \cdot e_2 = \overline{(\overline{e_1} + \overline{e_2})}$$

This is easily checked by setting up the truth table. The NOR operator is obtained from the OR circuit by inversion of the output. If an OR operator is available, which also possesses the inverse output, i.e.

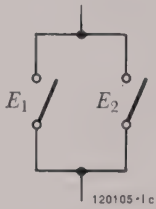
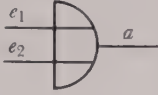
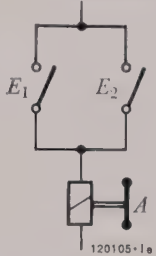
Operator	Relay circuit	Symbol	Truth table		
AND		 $e_1 \cdot e_2 = a$ 120105 · 1 b	e_1	e_2	a
			0	0	0
			0	1	0
			1	0	0
OR		 $e_1 + e_2 = a$ 120105 · 1 d	0	0	0
			0	1	1
			1	0	1
			1	1	1
NOR		 $\overline{e_1 + e_2} = a$ 120105 · 1 f	0	0	1
			0	1	0
			1	0	0
			1	1	0

TABLE I

Relation of two logic signals

- E

=

Inputs to relay circuits

e

=

Corresponding inputs to logic circuits
- A

=

Outputs from relay circuits
- a
- =
- Corresponding outputs from logic circuits

the NOR function, it is possible to realize all AND and OR relations with this one element. This component is included in the standard programme of the Brown Boveri electronic system as a printed circuit. Thus the circuit can be assembled neatly with a minimum of alternative hardware.

Tables II and III show further examples of logic operators, such as signal retarder, signal blocker, analogue-to-digital converter and digital-to-analogue converter. The logic element used to suppress the figure-eight current in the two-converter connection consists of a combination of the above elements.

The input quantities for the logic unit are the two rectifier currents I_1 and I_2 , and the desired value for the current I_s . These three quantities are converted into logic signals in analogue-to-digital converters. The symbols i_1 and i_2 denote the logic signals for the first and second current, respectively, such that the value of i_1 is 1 when the current I_1 is present, and vice

versa. The desired value I_s is converted into the logic signal i_s , with the value 1 when I_s is negative. The control system allocates a positive desired value I_s to the current I_1 and a negative I_s to I_2 . Thus in the steady state $i_s=0$ corresponds to $i_1=1$ and $i_2=0$. For $i_s=1$ the situation is reversed, i.e. $i_1=0$, $i_2=1$. The blocking signals from grid control sets 1 and 2 are denoted by b_1 and b_2 , respectively.

This logic system therefore has three inputs, i_s , i_1 and i_2 , and two outputs b_1 and b_2 . The possible combinations of the inputs are shown in Table IV. These are allocated definite values of the outputs b_1 and b_2 , according to the manner of operation of the circuit in which the figure-eight current is suppressed. If the conditions are established for blocking the first grid control set in accordance with Table IV, the following equation is obtained:

$$b_1 = i_s i_1 i_2 + i_s i_1 i_2 + i_s i_1 i_2 + i_s i_1 i_2 + i_s i_1 i_2$$

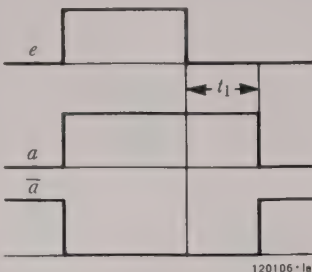
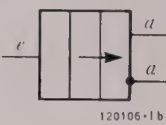
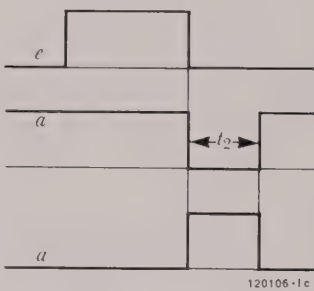
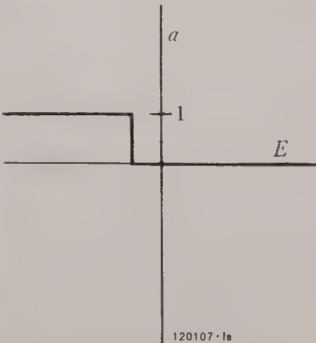
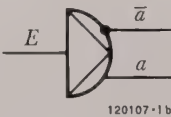
Signal retarder	 120106-1a	 120106-1b						
Signal blocker	 120106-1c	 120106-1d						
Analogue-to-digital converter	 120107-1a	 120107-1b						
Digital-to-analogue converter	<table border="1" data-bbox="380 1520 677 1837"><thead><tr><th>e</th><th>A</th></tr></thead><tbody><tr><td>1</td><td>- 15 V</td></tr><tr><td>0</td><td>+ 15 V</td></tr></tbody></table> 120107-1c	e	A	1	- 15 V	0	+ 15 V	 120107-1d
e	A							
1	- 15 V							
0	+ 15 V							

TABLE II

Elements of logic circuits

- e, a = Corresponding inputs and outputs of logic circuits
- $\bar{a}$ = Inverse signal to a
- t_1 = Time for which the 1-0 change of input e is delayed by the signal retarder
- t_2 = Time for which the 0 signal remains at output a when the input changes from 1 to 0

TABLE III

Elements of logic circuits

- E, A = Analogue input and output signals
- e, a = Logic input and output signals

Simplifying this according to the rules of Boolean algebra, we obtain

$$b_1 = \bar{i}_1 i_2 + i_1 \bar{i}_2 + i_s \bar{i}_1 \bar{i}_2 \\ = i_2 + (i_s \bar{i}_1 \bar{i}_2)$$

A further substitution leads to

$$b_1 = (i_s \bar{i}_1) + i_2$$

This equation states that the first grid control set will be blocked either when the desired value is negative and I_1 simultaneously zero, or when I_2 is present. It is free to operate when I_s is positive and I_2 has disappeared. Accordingly, for the blocking signal for the second grid control set:

$$b_2 = (\bar{i}_s \bar{i}_2) + i_1$$

These relationships for b_1 and b_2 can be realized by means of NOR and OR operators. The equations can then be rewritten

$$b_1 = \overline{(\bar{i}_s + i_1)} + i_2 \\ b_2 = (\bar{i}_s + i_2) + i_1$$

The equation for b_1 states that $\bar{i}_s$ and i_1 have to be applied to a NOR gate; the output of this operator should be applied with i_2 to an OR gate, at the output of which the signal b_1 stands. As the equation for b_2 shows, the appropriate relationship applies for it. The manner in which these two relationships are put into effect is illustrated in Fig. 4. This sketch also includes the two signal retarders, whose task is to hold up the release of the grid control sets. During this time-lag the converter which has just ceased to carry current must have time to regain its full blocking capacity. The signal retarders delay the 1-0 change of the signals b_1 and b_2 by the interval t , which is usually between 6 and 10 ms.

Fig. 5 shows the signal programme for the change from current 1 to current 2 and back. The possible states or combinations of the signals i_s , i_1 and i_2 are denoted therein and in Table IV by the letters a to f. The exceptional state in which both currents are flowing (g and h in Table IV), which is equivalent to the presence of a figure-eight current, causes both grid control sets to be blocked, thereby suppressing the figure-eight current.

The oscillogram in Fig. 6 illustrates the process of reversing the current in the armature of a motor. Reading downwards from the top, the signals i_s , i_1 ,

TABLE IV

i_s	i_1	i_2	b_1	b_2	Operational state (see Fig. 5)
0	0	0	0	1	f
0	0	1	1	0	e
0	1	0	0	1	a
0	1	1	1	1	g
1	0	0	1	0	c
1	0	1	1	0	d
1	1	0	0	1	b
1	1	1	1	1	h

Possible combinations of the three input signals i_s , i_1 and i_2 of the logic circuit of the two-converter connection with suppressed figure-eight current, and the associated states of the output signals b_1 and b_2 . The letters in the right-hand column refer to Fig. 5; a-f are operational states, g and h exceptional states.

i_2 , b_1 and b_2 can be seen. At the bottom the current is shown as an analogue signal. The states a-d in Fig. 5 are repeated on the oscillogram. A negative voltage of the logic signal corresponds to the value 1.

For d.c. drives it is often extremely important to be able to reduce the speed of the motor reliably to zero. Typical examples of drives of this kind are

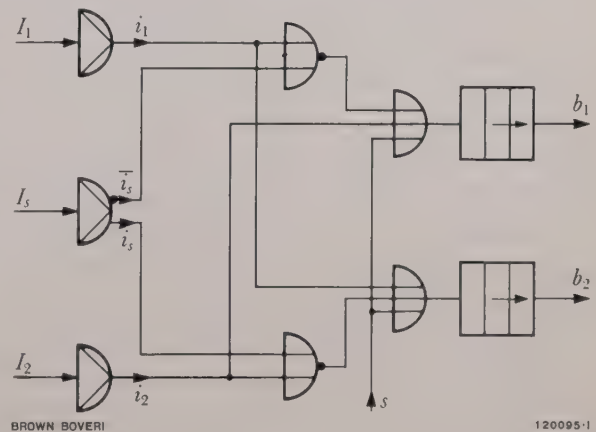


Fig. 4. - Schematic diagram of the logic unit used for suppressing the figure-eight current in a two-converter connection

- I_1, I_2 = Converter currents
- I_s = Desired value for current
- i_1, i_2 = Logic signals for converter currents
- i_s = Logic signal for desired current
- $\bar{i}_s$ = Inverse signal to i_s
- b_1, b_2 = Logic blocking signals for grid control sets 1 and 2
- s = Logic current-blocking signal

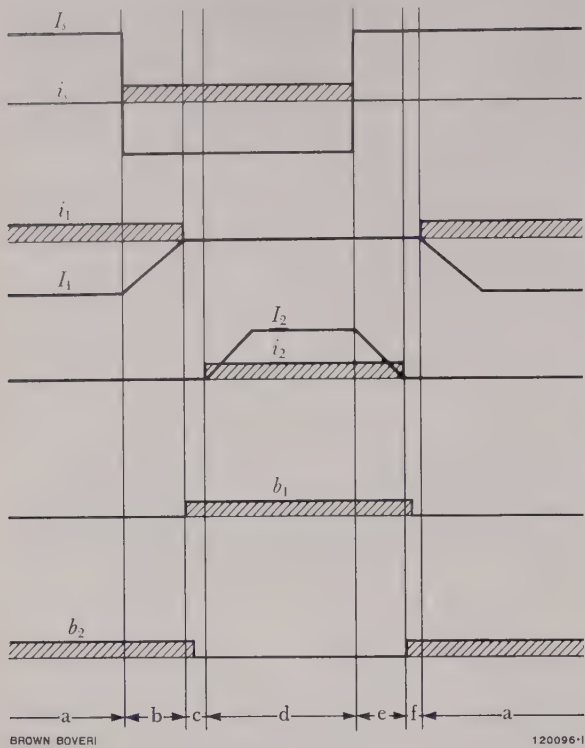


Fig. 5. – Diagrammatic representation of the desired and actual values of the current I_s , I_1 and I_2 , their logic signals i_s , i_1 , i_2 and the grid blocking signals b_1 , b_2 in a two-converter connection with suppressed figure-eight current

The hatched areas denote the value 1 of the logic signals belonging to the analogue quantities

a–f = Operational states

blooming and cold-strip mills, and coiler drives. The problem of control to zero speed may be reduced to the problem of controlling to zero current. If care is taken to ensure that current cannot flow, the motor can no longer rotate. In installations with only one direction of rotation, and thus with only one rectifier, it is quite an easy matter to control to zero current. It is only necessary to reverse the polarity of the desired value for the current and the rectifier will be completely blocked. The same principle can also be employed with two-converter connections. A stop signal s , given as a logic signal at the desired moment, stops the flow of current in the converter momentarily carrying current, and thus reliably brings the drive to a standstill.

As an additional safety measure, the grid control sets of the two converters are blocked directly. The

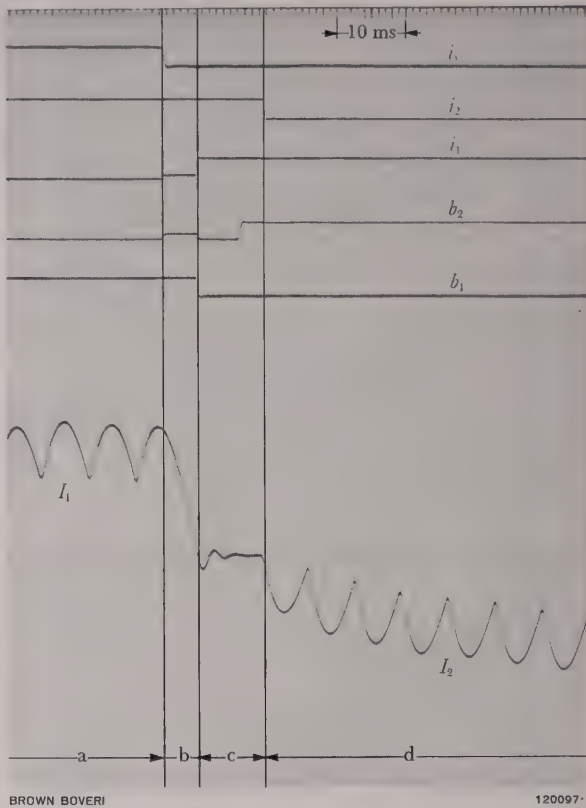


Fig. 6. – Oscillogram of the current changeover, from one converter to the other in a two-converter connection with suppressed figure-eight current

At current zero a short time-lag of a few milliseconds is inserted (recovery time) to allow the converter to recover its blocking capacity.

- i_s = Logic signal for desired current
- i_1, i_2 = Logic signals for converter currents
- b_1, b_2 = Logic signals blocking grid control sets of the converters 1 and 2
- I_1, I_2 = Currents of the converters
- a–d = Operation states (see Fig. 5)

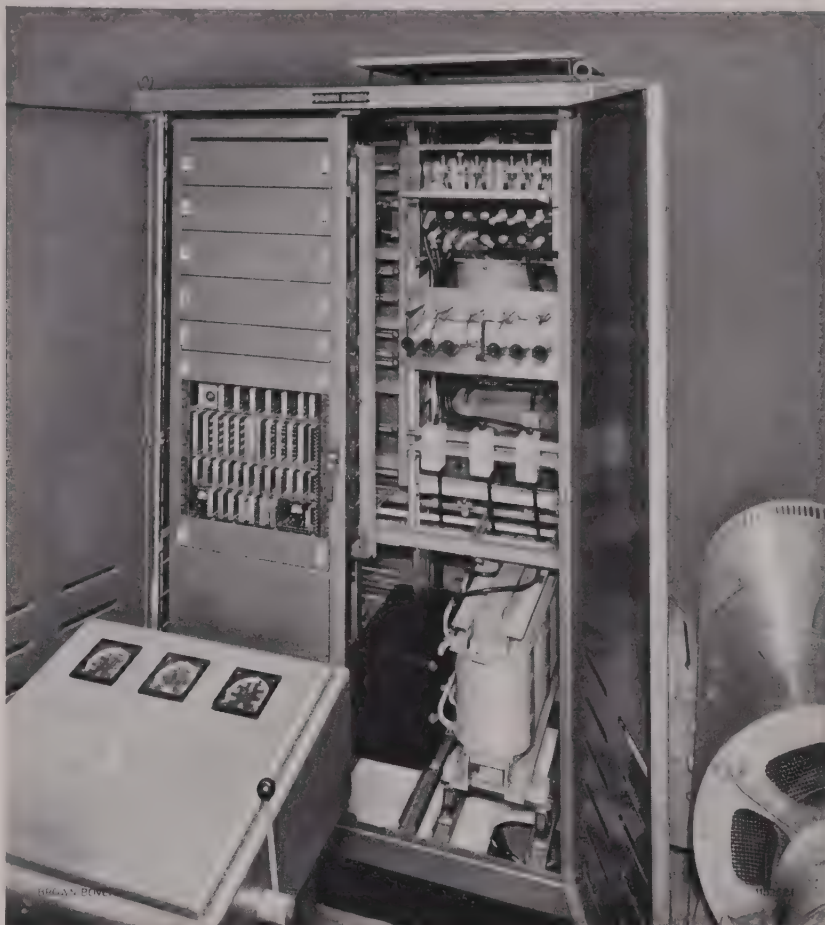
conditions for blocking, as formulated earlier, now have to be extended and become

$$b_1 = (\overline{i_s + i_1}) + i_2 + s$$
$$b_2 = (\overline{i_s + i_2}) + i_1 + s$$

The exact stop signal is also included in the logic diagram in Fig. 4. It represents the realization of the above equations. This absolute blockage of the current is not usually stipulated for systems exclusively controlling current. But it is most important for speed control systems when the ability to stop definitely is stipulated for safety reasons.

Fig. 7. — 30-kW reversing drive used, for instance, for the screwdown gear of a rolling mill; equipped with silicon thyratrons type CS 100 in a three-phase anti-parallel connection with suppressed figure-eight current

Visible at the top of the right-hand half of the cabinet are the silicon thyratrons. In the hinged frames of the left-hand half (from top to bottom): tiers containing the gate controls, changeover logic unit, current control and speed control.



Practical Applications for Armature and Field Supply

The foregoing chapters dealt with the functions of the current control system used for two-converter connections in which the figure-eight current is suppressed. The rest of this article will be devoted to its application in special cases. Here a distinction must be made between armature and field supply. In the examples which follow, the current is assumed to change continuously.

Armature Feed

by Two-Converter Connection with Suppressed Figure-Eight Current and Speed Control

The equipment for this system is illustrated in Fig. 7, its circuit diagram in Fig. 8. Cascaded into the well-known current loop is a speed loop. The positive and negative limits of the output of the speed

amplifier fix the maximum admissible positive and negative armature current. The desired value of the current can be influenced direct by signal B from the logic element and the current reliably reduced to zero, thus stopping the motor. The changeover from one converter to the other in the case of armature supply is effected as follows:

Suppose the motor is rotating with a positive speed and positive desired value for the current, supplied by converter 1. If the desired speed is suddenly changed from n^* , and made negative, I_a changes direction. Thus, on the one hand, the actual value of the current is reduced to zero at once by the control system, while on the other hand the logic signal i_d changes in magnitude. This yields one of the conditions for switching over to converter 2. The second condition is fulfilled as soon as i_d becomes zero. The first grid control set is blocked, the second being released after a time-lag. The control system

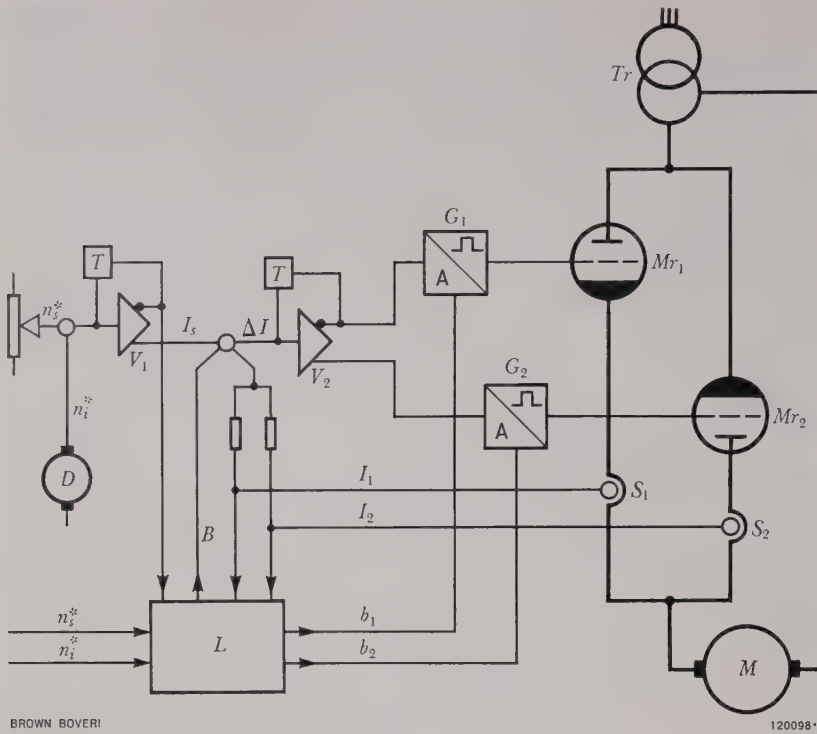


Fig. 8. - Speed control when the motor armature is fed by anti-parallel converters, the figure-eight current of which is suppressed

- Tr = Transformer
- M = Motor
- Mr_1, Mr_2 = Converters
- D = Tacho-generator
- S_1, S_2 = Current transformers
- G_1, G_2 = Grid control sets
- V_1 = Speed control amplifier
- V_2 = Current control amplifier
- T = Stabilizing filters
- L = Logic unit for change-over
- n_i^* = Desired value for speed
- n_i = Actual value of speed
- I_s = Desired value of current
- I_1, I_2 = Actual currents of the two converters
- ΔI = Current deviation
- B = Stop signal
- b_1, b_2 = Logic signals blocking the grids of converters 1 and 2

now operates through converter 2, braking the motor by shifting the grid pulses to the right, then accelerating it to the desired negative speed by shifting the pulses

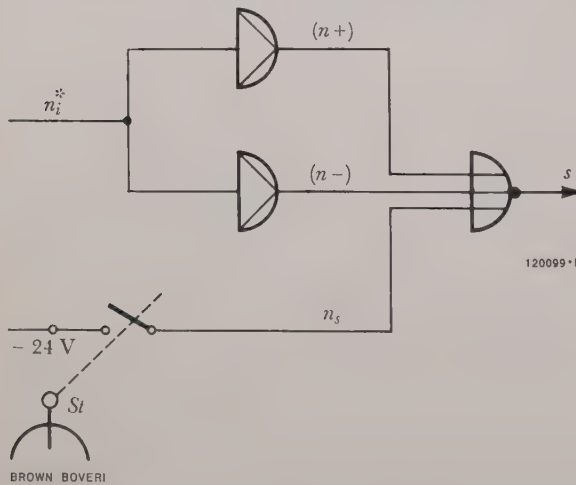


Fig. 9. - Conditions for standstill

The logical signal s assumes the value 1 when the control lever is on 0 and the speed of the motor is in a small band close to zero.

- n_i^* = Motor speed
- $(n+)$ = Logic signal for positive speed
- $(n-)$ = Logic signal for negative speed
- n_s = Logic signal for desired speed (as given by control lever St)

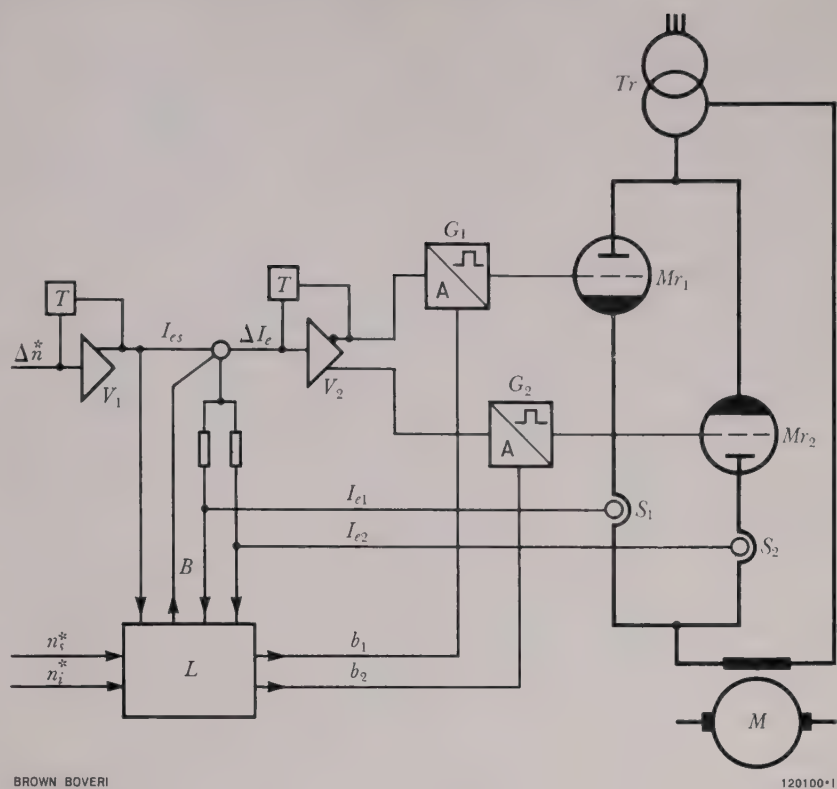
to the left. If the machinist only wishes to make a slight correction to the speed, by reducing the desired value but not reversing its direction, the desired value of the current changes its direction again, provided the rate of change of desired speed is sufficiently rapid and the motor load is small. As for speed reversal, converter 2 takes over the task of carrying the current and brakes the motor by shifting the grid pulses until the desired speed is reached. Having attained the required speed, I_s becomes positive again. Afterwards, when the current of the second converter has become zero, converter 1 takes over and runs the motor up to the same speed.

To ensure that the drive stops properly, the motor current is blocked as soon as the speed setting is zero and the actual speed is within a very narrow band in the region of zero. The actual speed of the machine is converted into separate positive and negative logic signals according to the direction. If the speed is sufficiently positive, $(n+) = 1$; if sufficiently negative $(n-) = 1$. In a selected range in the region of zero speed, amounting to approximately $\pm 1\%$ of the rated speed, both show 0. The logic signal of the desired speed value drops to 0 as soon as the control lever is set on zero. The signal s for blocking the

Fig. 10. – Contiflux field control with anti-parallel converters and suppressed figure-eight current

An example of continuous control

Tr = Transformer
 M = Motor
 Mr_1, Mr_2 = Converters
 S_1, S_2 = Current transformers
 G_1, G_2 = Grid control sets
 V_1 = Amplifier for speed deviation Δn
 V_2 = Excitation current amplifier
 T = Stabilizing filters
 L = Logic unit for change-over
 n_i^* = Desired speed
 n_i = Actual speed
 Δn^* = Speed deviation
 I_{es} = Desired excitation current
 I_{e1}, I_{e2} = Currents of the two converters
 ΔI_e = Current deviation
 B = Current-blocking signal
 b_1, b_2 = Logic signals blocking the grids of converters 1 and 2



current therefore has to fulfil the equation

$$s = \overline{n_s} \cdot \overline{(n+)} \cdot \overline{(n-)}$$

This equation can be converted into the NOR form, in which case it becomes

$$s = \overline{n_s + (n+) + (n-)}$$

The realization of this is illustrated in Fig. 9.

Continuous Field Supply with Two-Converter Connection with Suppressed Figure-Eight Current

The main field of application for continuous field supply is Ward-Leonard drives with field control of the generator, and for drives employing the Contiflux system of control. Continuous field control may be defined as that form of control which permits any positive or negative field current. The instructions for the changeover from one converter to the other are given by the control system itself, in that the desired value for the current is utilized as a logic signal. As soon as this value changes its direction, the change to the second converter is initiated; it takes over the current, as soon as that of the first rectifier has disappeared. The principle of Contiflux

control is illustrated in Fig. 10. The desired value of the excitation current in the well-known current control loop is equal to the amplified speed deviation of the overriding speed control loop. The process of switching over the current is the same as for armature supply, with the difference that, on account of the field strength, it takes longer for the current to drop to zero.

The current-blocking signal s can likewise be used to reduce the field current to zero when the condition for standstill

$$s = \overline{n_s} \cdot \overline{(n+)} \cdot \overline{(n-)}$$

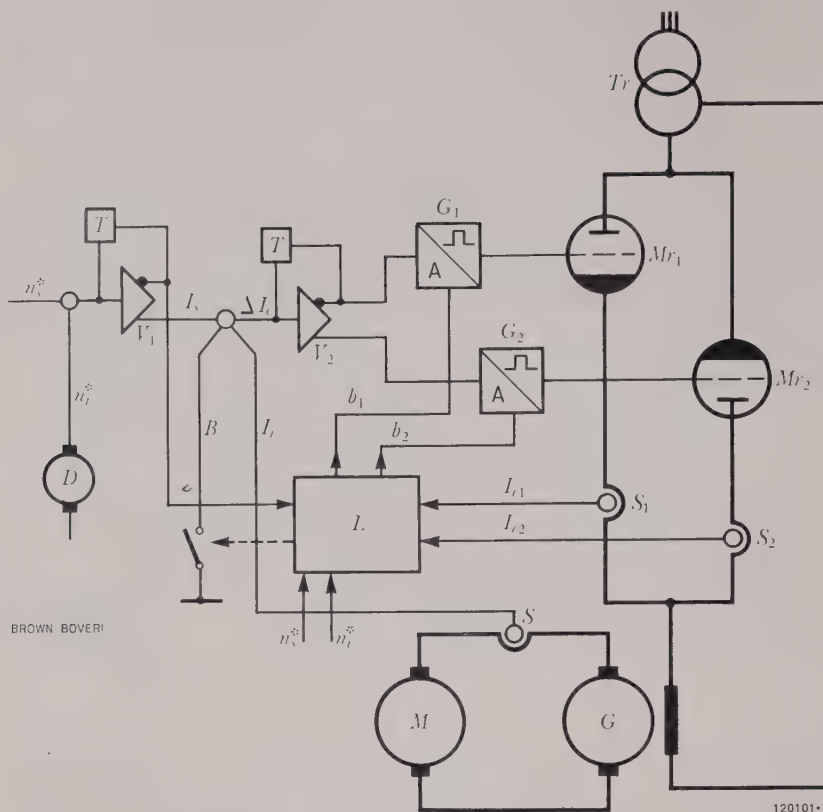
is fulfilled. This ensures that the field is not kept switched on unnecessarily, especially when the drive remains at rest for a long time.

The field supply for reversible Ward-Leonard drives is depicted in Fig. 11. The excitation current of the generator is not controlled. The two rectifier currents only enter the logic element as signals. As a third input the desired value of the armature current is used. The principle of operation is exactly the same as in the current control system dealt with earlier.

Fig. 11. — Ward-Leonard drive with field supplied from a two-converter connection with suppressed figure-eight current

An example of continuous control

- Tr = Transformer
- M = Motor
- Mr_1, Mr_2 = Converters
- G = Ward-Leonard generator
- D = Tacho-generator
- S = Armature current transformer
- S_1, S_2 = Current transformers for the converter currents
- G_1, G_2 = Grid control sets
- V_1 = Speed control amplifier
- V_2 = Armature current control amplifier
- T = Stabilizing filters
- L = Logic unit for change-over
- n_s^* = Desired speed
- n_i^* = Actual speed
- I_s, I_i = Desired and actual armature current
- I_{e1}, I_{e2} = Currents of the two converters
- ΔI_e = Current deviation
- B = Current-blocking signal
- b_1, b_2 = Logic signals blocking the grids of converters 1 and 2



If the Ward-Leonard drive has to be stopped, the criterion considered hitherto is not sufficient. If the excitation current of the generator is reduced to zero, the motor can nevertheless continue to rotate owing to the remanence of the generator. Complete standstill can only be attained when the desired value of the armature current is made exactly zero, which can, for instance, be realized with a contactless switching element.

Discontinuous Field Supply with Two-Converter Connection with Suppressed Figure-Eight Current

For reversing drives with field reversal, the latter process is usually discontinuous. In order to attain short reversing times for the motor, the direction of the field must be changed as rapidly as possible. In this application the primary duty of the logic element is reversing the direction of the field, which has to be changed from a positive to a negative value as soon as an external signal, in this case Δn , demands. The

change from the one direction to the other is discontinuous. In order to obtain as short a reversing time as possible, the system operates with a large voltage reserve, amounting to 4–6 times the rated voltage, for super-excitation. The control system in this case is illustrated by Fig. 12.

The desired value of the excitation current always has the same polarity and the same magnitude. The control system acts on the two converters in the same sense. The decision regarding the direction of the current is made by the logic unit. The inputs to the latter are Δn^* , the deviation of the actual speed of the motor from the desired value, and the two converter currents. The outputs are once more the blocking signals b_1 and b_2 for the grid control sets 1 and 2, as well as a common inversion signal w applied to both sets at once. Supposing that, at the start of field reversal, rectifier 1 is carrying current, the changeover procedure is roughly as follows: The control lever is thrown in the opposite direction. This changes the sign of Δn^* and the logic unit immediately gives the

instruction for the first grid control set to change to inversion. Since converter 2 is still blocked, the inversion signal has no effect on its grid control. The voltage of converter 1 becomes completely negative, thus allowing the current to attain its maximum rate of change and the field to be de-energized as rapidly as possible, though the control system plays no part in the latter action. The decreasing actual current which is an input to the control system causes the field-control amplifier to be completely open-circuited. At its output, and thus at the inputs to the two grid control sets, signals appear representing 100% rectification by the converters. Owing to the direct instruction for inversion, the current rapidly becomes zero, whereupon the first grid control set is blocked and the inversion signal withdrawn. The second set is released after the usual time-lag to accept the full control signal. The full rectification voltage of the second converter now appears at the field winding of the motor, the current in which is built up to its maximum in a very short time. The control system limits the current to the predetermined level. The logic unit for this kind of two-converter connection with suppressed figure-eight current

must therefore have an additional output signal giving the direct instruction for inversion; this may be denoted by w . Belonging to every Δn^* in steady-state operation there is a definite direction of the excitation current. Suppose now the same assumptions are made regarding Δn as were made for i , previously. When $\Delta n=0$, $i_1=1$ and $i_2=0$ should apply, while for $\Delta n=1$, $i_1=0$ and $i_2=1$. The inversion signal must be 1 when these normal conditions are not fulfilled, that is to say, when Δn has changed to 1, but the first current i_1 is still rising to 1. As soon as w assumes a value of 1, the grid pulses will be displaced as far as possible to the right, i.e. towards inversion. The equation for the logic signal is then of the form

$$w = \Delta n \, i_1 + \overline{\Delta n} \, i_2$$

To transform this expression simply so that it fulfils the NOR requirements, we may write

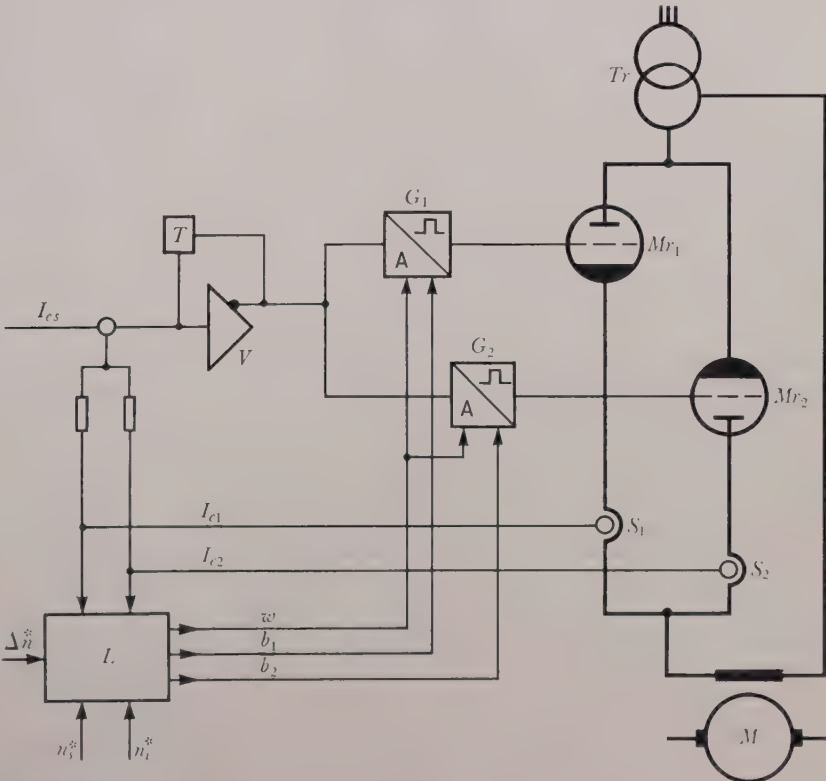
$$w = \overline{(\Delta n + i_1)} + \overline{(\Delta n + i_2)}$$

The two expressions $\overline{\Delta n + i_1}$ and $\overline{\Delta n + i_2}$ are already known from the logic element described earlier. They are now applied to the NOR gate, at the output of

Fig. 12. – Supply of a drive with field reversal, using anti-parallel converters with suppression of the figure-eight current

An example of discontinuous control
 V = Control amplifier for excitation current
 I_{es} = Desired value for excitation current
 w = Logic signal giving direct instructions to the grid control sets for inversion

All other notation as in Fig. 11.



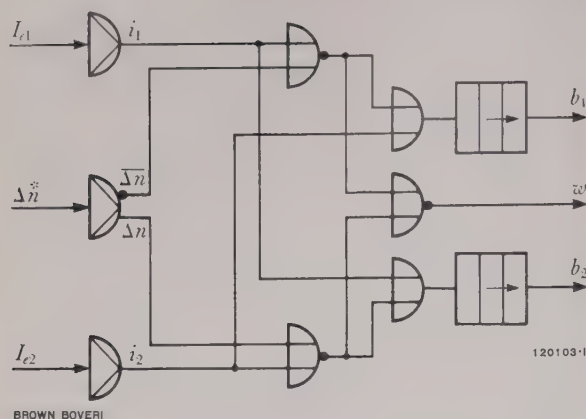


Fig. 13. — Schematic diagram of the logic unit for a two-converter connection with suppression of the figure-eight current (discontinuous field supply)

I_{e1}, I_{e2} = Converter currents

Δn^* = Deviation of motor speed

i_1, i_2 = Logic signals for the currents

Δn = Logic signal for the deviation Δn^*

$\overline{\Delta n}$ = Inverse signal to Δn

b_1, b_2 = Blocking signals for grid control sets 1 and 2

w = Logic signal giving direct instructions to the grid control sets for inversion

which the signal w stands. The extended logic unit is shown schematically in Fig. 13. The criterion for standstill can reduce the excitation current to zero directly via the inversion inputs of the grid control sets.

The oscillogram in Fig. 14 shows the logic signals and the current and voltage as recorded in practice. Reading downwards the following quantities are shown as logic signals: The reversal signal Δn , the two currents i_1 and i_2 , the blocking signal for the two grid control sets b_1 and b_2 , and the inversion signal w , which displaces the control pulses completely to the right. When these logic quantities have a negative voltage, this corresponds to the value 1. The lower half of the oscillogram shows the current and voltage. At the same time as the reversal signal Δn is given, the instruction for inversion is given to the first grid control set. The voltage immediately changes sign and the current decreases to zero at the maximum rate. As soon as it has reached zero, the

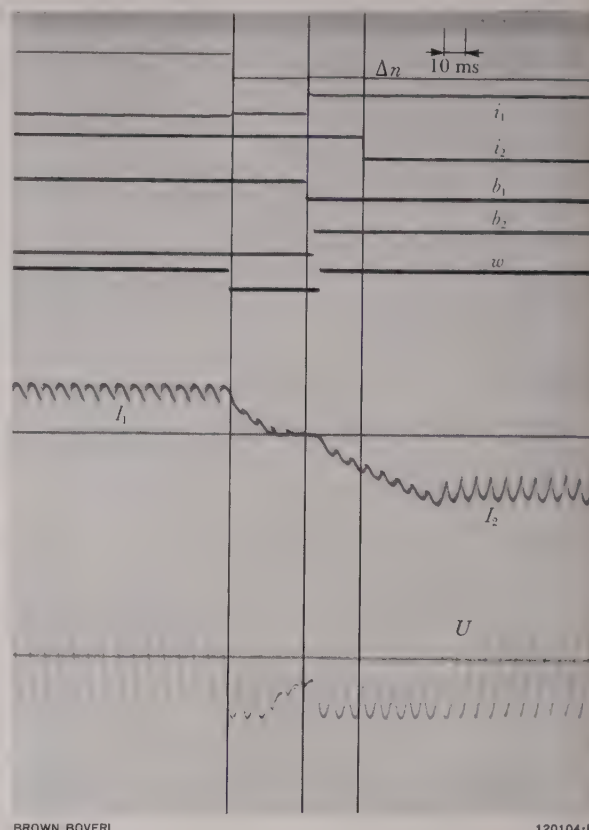


Fig. 14. — Oscillogram of current changeover from one converter to the other in anti-parallel connection with suppression of the figure-eight current, assuming an inductive load

When the first current reaches zero, a short recovery time-lag is inserted before the second current is allowed to flow.

Δn = Logic signal for the motor speed deviation

i_1, i_2 = Logic signals for the two converter currents

b_1, b_2 = Logic signals blocking the converter grids

w = Logic signal for inversion

I_1, I_2 = Currents of the two converters

U = Voltage across the inductance

first grid control set is blocked; the signal retarder controlling the second set starts and releases its control set on expiry of the time-lag; the inversion signal is cancelled, allowing the second converter to produce the full rectification voltage. It causes the current to build up to the preset value in the optimum time. When the logic signal 1 appears for the second current, the process of reversal is finished.

(KME)

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A PHOTO-ELECTRIC LOOP-MEASURING DEVICE

621.317.799.082.52:621.771.2

Considering an example of loop control as employed in continuous hot-rolling mills, the article describes a new contactless device for measuring the loop, by means of which a loop is represented by an electrical quantity.

CONTINUOUS hot-rolling mills are normally subdivided into a number of groups of stands. Whereas the roughing train often works on a multi-strand basis, the finishing stands are usually single-strand, in order that the final product may be kept true to gauge by eliminating tension from the rolling process. A sure method of ensuring that no tension is exerted on the material between two successive rolling stands is to allow it to form a loop. The size of this loop is normally kept constant by controlling the speed of the succeeding rolling stand.

For a loop to be controlled it is essential to be able to measure the size of the loop. Various methods are known, which permit the loop to be represented by a voltage. A method frequently employed (Fig. 1) is based on mechanical sensing with the aid of a looper,

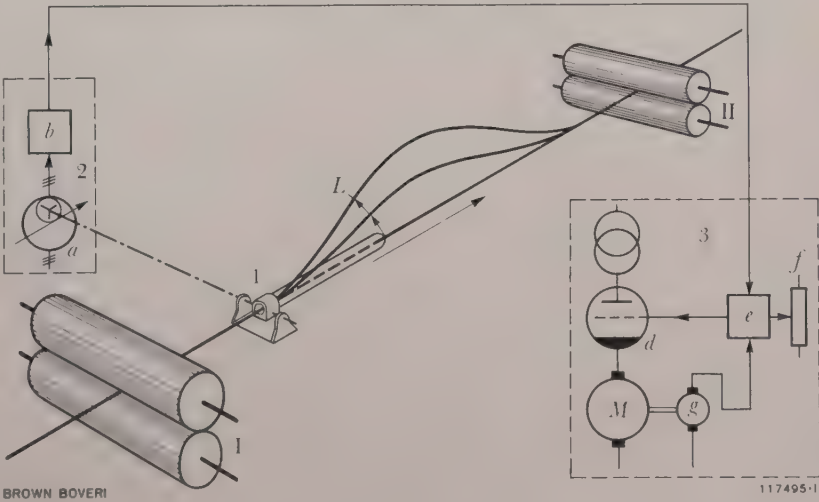
with a servo *a* connected to the shaft. Depending on the size of the loop, the servo produces a voltage proportional to the deflection of the looper, fed via a discriminator *b* as correction into the speed control circuit of the succeeding drive [1]. This system has proved very successful at rolling speeds up to 20 m/s.

During the development of the new Brown Boveri loop-measuring device, one guiding rule was kept constantly in mind: the variable height of a loop should be expressed by electrical quantities which correspond to the standardized signals of the Brown Boveri electronic system. The output should not be affected by variation of the temperature. The measuring device should function without contacts, free from inertia, and should possess no moving parts liable to wear, or any supplementary elements. The device must also be mounted simply and expediently.

The principle of the control system will now be explained with reference to Fig.2. The infra-red radiation from the hot material acts as the input quantity on a number of photodiodes in the measuring

Fig. 1. - Principle of loop control with mechanical looper

- I = Rolling stand
- II = Succeeding stand after the loop
- 1 = Mechanical looper
- 2 = Loop measurement
- a* = Servo
- b* = Discriminator
- 3 = Controlled motor driving the succeeding stand
- d* = Controlled rectifier
- e* = Controller
- f* = Reference-value unit
- g* = Tacho-generator (providing the actual value)
- M* = D.C. motor
- L* = Loop in three positions: taut, normal, slack



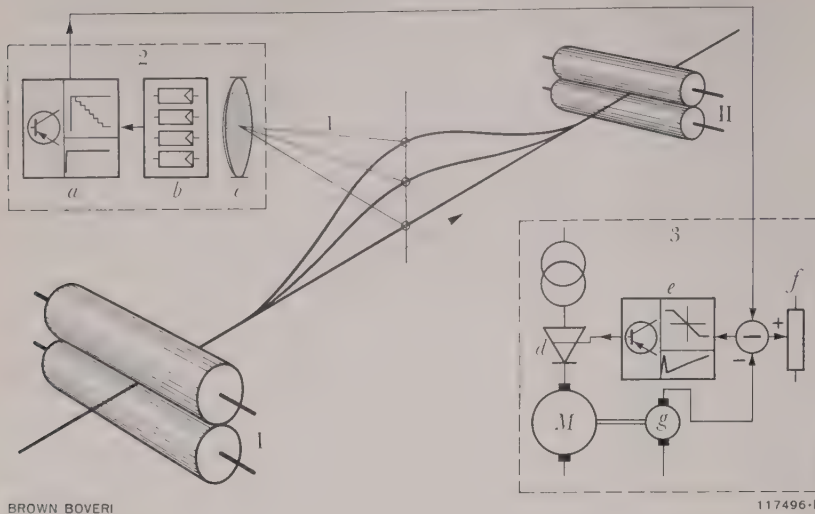


Fig. 2. - Principle of contactless loop control

- I = Rolling stand
- II = Succeeding stand after the loop
- 1 = Infra-red rays from the glowing material
- 2 = Loop measurement
 - a = Measuring device
 - b = Photodiodes
 - c = Condenser lens
- 3 = Controlled motor driving the succeeding stand
 - d = Controlled rectifier
 - e = Controller
 - f = Reference-value unit
 - g = Tacho-generator (providing actual value)
- M = D.C. motor

device. But only the culmination point of the loop is evaluated. Depending on the angle of incidence α of the rays, the device emits a proportional direct voltage containing no ripple, $U=f(\alpha)$. This voltage represents the actual value of the loop and influences the speed control of the drive following the loop.

The simplified circuit diagram of the loop-measuring device is shown in Fig. 3. The infra-red rays from the observed loop are focussed by a lens in the sensing head and made to strike one of the photodiodes, according to the angle of incidence. The effect of the light is to cause a current to flow in the

diode, which, as soon as it attains a certain magnitude, triggers an analogue-to-digital converter; the output potential suddenly changes from the value "0" to "1", both of which are standardized values. The converter is a trigger unit whose output is either 0 or 1 (see Fig. 4), depending on the input value. Thus the analogue input signal is converted into a digital output signal. Following the converter is a capacitor which differentiates the change in the output signal. Thus, when the photodiode is illuminated, a control pulse is produced. Fig. 4a shows the various stages of the signal conversion.

Analogue signal from the photodiode

Signal block with steep flanks

Differentiation of the block to yield pulses.

The pulses produced when light ceases to strike a diode are suppressed, while those produced when light strikes a diode are fed through OR gates to all digital stores [2]. The digital signal stores perform the functions of relays (Fig. 5). A control pulse at the 0 input (Fig. 5a, b) corresponds to the operation of the 0 contact in the relay circuit; and conversely, a 1 pulse corresponds to operation of the 1 contact. Thus an input pulse causes each digital store to assume the state 0 or 1, an analogue voltage being tapped off the subsequent voltage divider according to the state (Fig. 6).

The value of the input instruction and the output state of the digital stores are related to one another

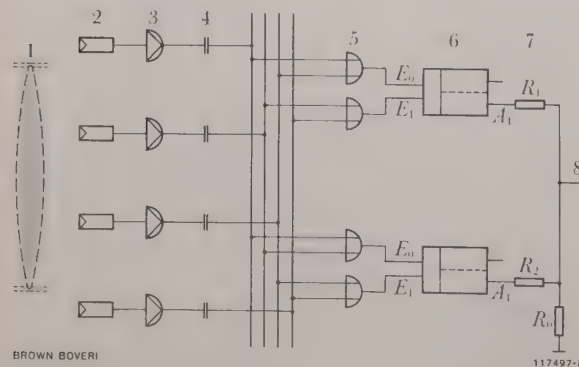


Fig. 3. - Simplified circuit diagram of the loop-measuring device

- 1 = Condenser lens
- 2 = Photodiodes
- 3 = Analogue-to-digital converter
- 4 = Differentiating element
- 5 = OR gate
- 6 = Signal store
- 7 = Voltage divider with the resistors R_0, R_1, R_2
- 8 = Output
- E_0, E_1, A_1 , see Fig. 5

by a binary system, i.e. the code [3]. The corresponding device contains 16 photodiodes (input elements). With the aid of four digital signal stores, each with two states, it is possible to obtain a total of $2^4 = 16$ switching combinations. The allocation of photodiodes to the respective state of each of the four signal stores is tabulated below:

Photodiode input	Digital signal store				
	No. Value	IV 8	III 4	II 2	I 1
0		0	0	0	0
1		0	0	0	1
2		0	0	1	0
3		0	0	1	1
4		0	1	0	0
5		0	1	0	1
6		0	1	1	0
7		0	1	1	1
8		1	0	0	0
9		1	0	0	1
10		1	0	1	0
11		1	0	1	1
12		1	1	0	0
13		1	1	0	1
14		1	1	1	0
15		1	1	1	1

To represent an output voltage corresponding, say, to the input “6”, the code signal 0 1 1 0 is obtained. Adding the relevant values together, we obtain $0 + 4 + 2 + 0 = 6$. By appropriate choice of the resistors $R_0 - R_4$, a stepped voltage (Fig. 7) is obtained at the output of the loop-measuring device.

The output voltage of the loop-measuring device is only changed when one of the photodiodes receives light. If the loop becomes too large, it exceeds the field of view of the device and the maximum output voltage remains as it was, thus influencing the succeeding drive in the correct sense. The output voltage also remains as it was when the radiation falls between two photodiodes. Likewise, the output is not affected when the brightness or quantity of light

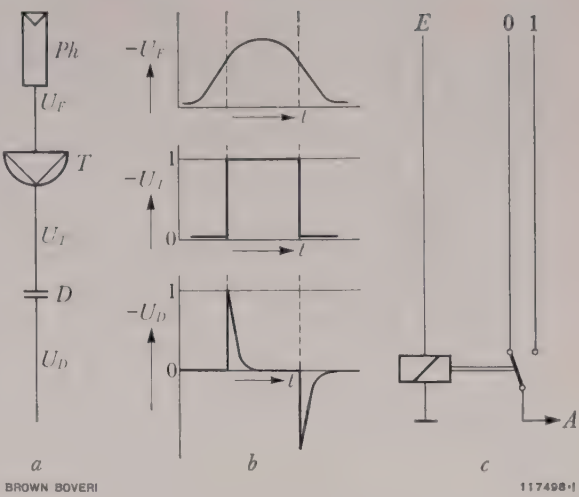


Fig. 4. - Explanation of pulse formation

- a: Symbols
Ph = Photodiode
T = Analogue-to-digital converter (trigger)
D = Differentiating capacitor
 U_F = Analogue signal at trigger input
 U_T = Signal block at trigger output
 U_D = Differentiated signal pulse
- b: Characteristic
- c: Equivalent relay circuit
E = Input
A = Output

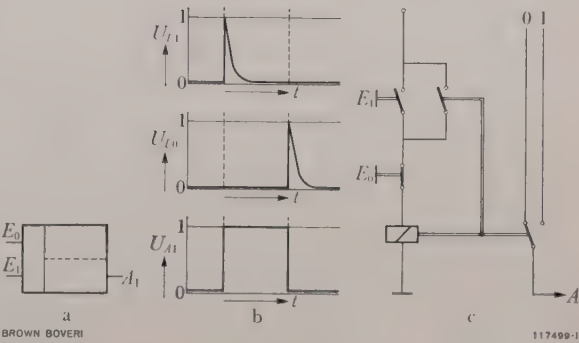


Fig. 5. - Digital signal store

- a: Symbols
 $E_0 = 0$ input
 $E_1 = 1$ input
 $A_1 = 1$ output
- b: Characteristic:
 U_{E0}, U_{E1}, U_{A1} = Voltages in function of time
- c: Equivalent relay circuit

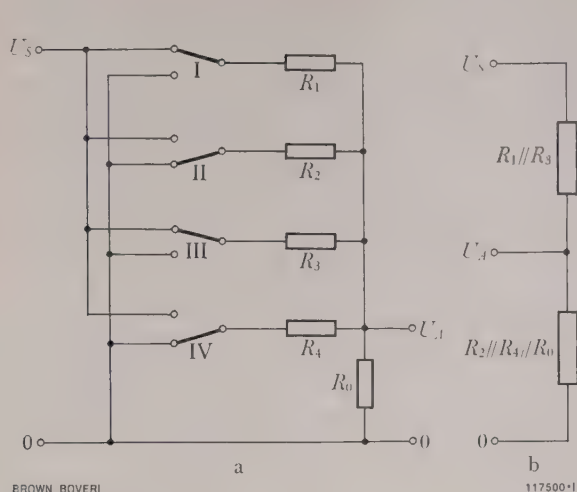


Fig. 6. - Digital-to-analogue converter

a: Simplified diagram with contacts

b: Equivalent circuit diagram

U_S = Supply voltage

U_A = Output voltage

0 = Zero line

R_0 - R_4 = Resistors

I-IV = Digital signal stores, shown as contact elements in equivalent circuit diagram.

varies, i.e. when the temperature or cross-section of the rolling stock is different.

The device responds to the angle of incidence of the light rays, so that the measurable height of the loop is dependent on the distance at which it is mounted and on the optical system. With a system having a field of vision of $\pm 15^\circ$, the range of measurement is ± 30 cm at a distance of 1 m. If the field is $\pm 30^\circ$, the range will be ± 60 cm at a distance of 1 m. In order to protect the device against excessive heat radiation, provision is made for the connection of a water cooling system. The device is housed in a strong screening casing. Inside printed circuits are used, requiring only four leads altogether, for the power supply and the output. Stray light can only produce a pulse if it has a sufficiently high intensity in the infra-red part of the spectrum and if it occurs in the band observed. A wrong output signal produced by such a pulse would indeed cause the loop to deviate from its proper position, but only until the light from the loop strikes the next photodiode. Then the false output signal is cancelled, the loop control restoring the original state.

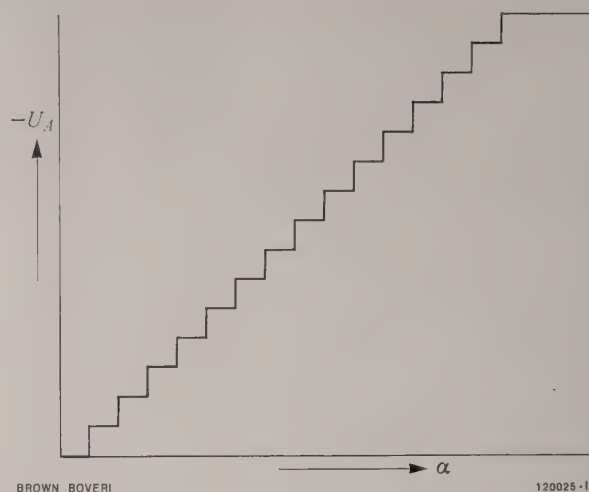


Fig. 7. - Characteristic of the loop-measuring device

α = Angle of incidence of the light

U_A = Voltage at output of the loop-measuring device

The loop-measuring device is perpendicular to the plane in which the loop moves. If, for example, looping tables are provided, the most convenient position for the device is below the table. The light rays pass through a slit to strike the photodiodes. This arrangement can be used for either horizontal or vertical looping tables.

In addition to the output voltage, which is proportional to any change in the size of the loop, a separate signal can be given for any position of the rolling stock within the limits of the measuring range. For instance, these signals may be used to perform the functions of limit switches. If the loop attains the maximum displacement, the signal causes a correction to be made to the speed of all the subsequent rolling stands.

By means of 'transfer inputs' it is possible to set output voltages independent of the light rays emitted by the glowing material. Transfer inputs are sets of contacts connected from outside, which, when actuated, apply a control pulse to one of the 16 different inputs, thereby compelling the allocated output voltage to be given. In this manner the normal output can be set while no material is running through the mill. The output value of this loop-measuring device can be introduced into the speed control of the succeeding stands in such a way that the desired loop size can be preselected on the control pulpit, or adjusted during rolling.

The loop-measuring device described can be extended, without enlarging its dimensions, allowing it to be used for determination of the position of any glowing material, e.g. detecting the edge of the material in broad-strip mills, or determining the position of the ingot or slab in automatically controlled reversing mills. To determine the position of material which is not glowing, e.g. cold strip, paper, plastics, etc., an auxiliary light source must be used.

Thus with this device, which functions without contacts or moving parts and requires no supple-

mentary elements, industry has an ideal unit available for positional control, adapted to the requirements of practical operation.

(KME)

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DIRECT HEATING OF BILLETS BY THE PASSAGE OF ELECTRIC CURRENT

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The direct method of heating elongated metal objects, particularly steel billets, by the passage of electric current is becoming increasingly popular in steelworks. The main reasons for this are the high efficiency during the heating process and the very short heating time. The present article describes the procedure of heating billets prior to rolling and the design of installations which serve this purpose; examples are given of completed installations.

THE GROWING interest being shown in resistance heating of billets prior to rolling may be explained by the advantages afforded, both from the metallurgical and the operational aspect, which were unattainable with conventional furnaces. This method of heating is ideal for elongated metal objects having a round or rectangular cross-section. With it billets with a cross-section of 30×30 to 120×120 mm and a minimum length of 1.2 m can be heated. The higher the ratio of length to cross-section, the more economical the operation of the installation. An average efficiency of about 80% is achieved by those installations completed so far, and this figure can be raised to 90% when the dimensions of the material are favourable. Such values cannot be achieved with the methods of heating employed hitherto.

Steel billets are heated from room temperature to the rolling temperature in a remarkably short time. The heating times vary according to the length and cross-section and at maximum power range from 30 to 200 s. This explains why the effect on the surface of the billet is so slight, the absence of scale greatly enhancing the quality of the finished product. There is no change in the structure of the steel; the formation of coarse grains and decarburization at the edges is avoided altogether. Despite the speed at which the billets are heated, hair-cracks are practically unknown, even in high-alloy steel.

Due to the passage of alternating current axially through the material, the heat is generated in the actual metal according to Joule's law. The result is that the heat is uniformly distributed over the cross-section with a very high efficiency.

Heater units for electric resistance heating are ready for operation at any time and do not require any pre-heating. In the event of a stoppage in the rolling mill the heater can be shut down until it is required again, and does not consume any energy during the idle period. As soon as the stoppage is ended, the heater is immediately ready again. Owing to its very short heating times, it fits ideally into

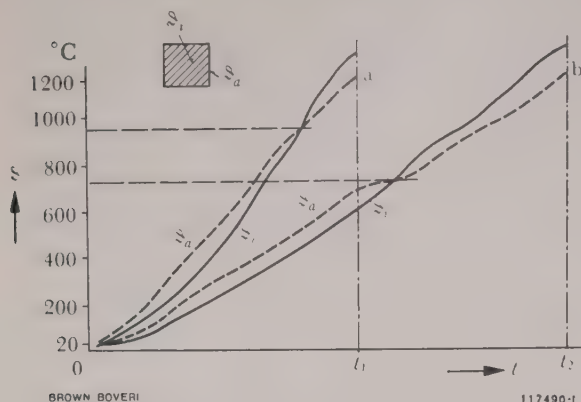


Fig. 1. — Curves of the temperature in the core ϑ_i and at the surface ϑ_a of billets heated by the direct passage of current, plotted in terms of the heating time t

the rhythm of a rolling mill or heat-treatment plant. The heater units are small in size and can therefore be accommodated with ease in an old plant where space is cramped. They are easy to control and do not require any special knowledge as they can be automatically controlled and thus fit well into automatic rolling mills.

At normal industrial tariffs the cost of electric heating is no higher than that of other methods. The method becomes much more economical though, particularly with high-grade steel, owing to the reduced amount of scale and the metallurgical advantages mentioned above.

An installation of this kind requires very little maintenance. The only parts exposed to greater wear than in other installations are the heavy-current contacts of the heater units, but these are easily replaced and, owing to their simple design, can be made up in the factory workshop.

Principle of Billet Heating

In resistance heating the alternating current supplied from the mains, after suitable transformation, is passed through the billet by special contacts. Owing to the electrical resistance of the billet, it is rapidly heated by the heavy current. As known from induction heating, the current flowing axially in the material produces an alternating magnetic field, which in turn produces a 'skin effect' at the surface of the material. This distribution of the current over

the cross-section produces a temperature curve characteristic of this method of heating (Fig. 1). At the beginning of the heating period the temperature at the surface ϑ_a (see Fig. 1) leads the temperature in the core ϑ_i , by quite an appreciable amount as long as the steel retains its magnetic properties. In the region of 600 °C the magnetic permeability decreases, assuming the value 1 at the Curie point.¹ The 'skin effect' is now less pronounced and the temperature in the core rises more rapidly. At the upper end of the temperature range, i.e. above about 700 °C, the loss of heat due to radiation becomes so considerable that ϑ_i in the core gradually catches up ϑ_a on the surface, in fact towards the end of the heating period it even exceeds it. The balance between the two temperatures in the region of the Curie point, as well as the temperature difference at the end of the heating time are a function of the heating time, as the curves a and b in Fig. 1 show. Since the possibility of attaining a temperature balance by conduction is very small when the heating times are so short, the point of intersection of the two curves tends towards higher temperatures with decreasing heating time. This form of heating ($\vartheta_i > \vartheta_a$) is unobtainable with any other method and yields ideal conditions for the subsequent deformation of the metal during rolling. This difference between the temperatures at the surface and in the core is therefore also utilized for quite small objects, such as forgings, although the efficiency is not so high as with the relatively long rolling billets.

Design of the Heating Installation

The layout of a heating installation of this kind is shown schematically in Fig. 2a. The main parts are the high-voltage switchgear, a single-phase variable transformer and the heater unit. The greatest difficulty was encountered with the switchgear because ordinary circuit-breakers could not be considered for 60 to 100 operations per hour. Up to powers of 2 MVA good results have been obtained with the high-voltage contactor rated 200 A at 10 kV. However, for higher powers a special arrangement

¹ The Curie point of a ferro-magnetic material is the temperature at which its magnetic properties vanish.

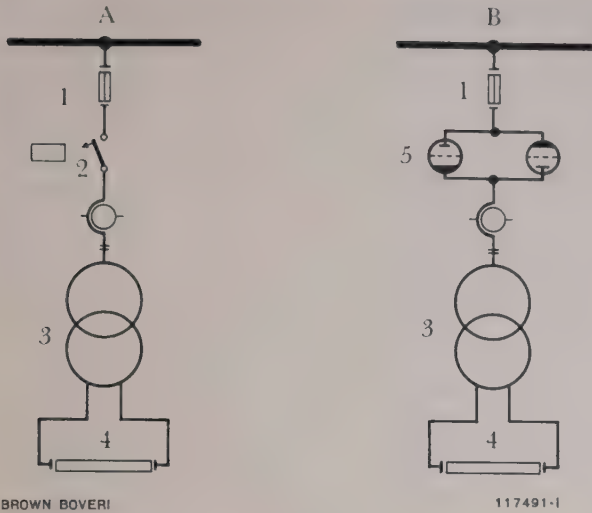


Fig. 2. – Block circuit diagrams of a billet-heating installation controlled by a contactor (A) or by mercury-arc converters (B)

- 1 = Fuses
- 2 = Air-break contactor
- 3 = Heating transformer
- 4 = Heating unit
- 5 = Mercury-arc converters acting as switch

has been developed, consisting of two grid-controlled mercury-arc rectifiers connected in anti-parallel, as illustrated in Fig. 2b, where each valve blocks one half-cycle of the alternating current. With this arrangement not only can heavier loads be handled, but also the moment of closing the circuit can be so controlled that the inrush surge of the transformer exerts a minimum influence on the supply mains. Installations with this form of control have proved very satisfactory in continuous operation.

One of the main difficulties in resistance heating is transporting the energy at relatively heavy currents up to about 40 kA from the secondary terminals of the transformer to the actual material. On the one hand care must be taken to ensure that the ohmic resistance of the leads is small compared with that of the material, because this governs the efficiency of the installation. On the other hand, owing to the heavy current, inductive voltage drops are produced in the leads, so that the transformer also has to supply reactive power. The stipulation that the ohmic and inductive resistances must be low is all the more difficult to fulfil, the greater the range of adjustment of the heater unit as regards the length of the billet. This factor has also to be taken into account with automatic heating installations in

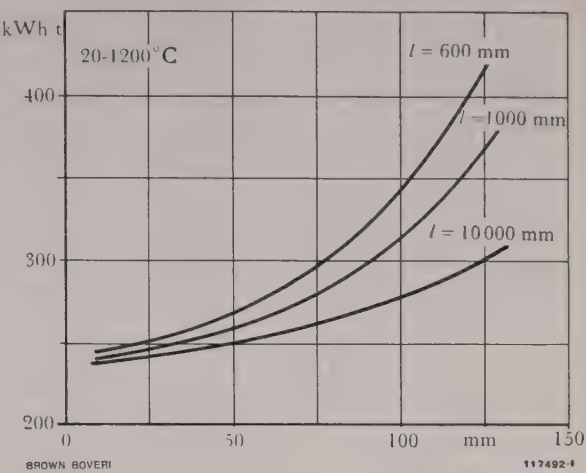


Fig. 3. – Mean energy consumption in kWh/t for heating steel billets of different lengths l by the direct passage of current, plotted in terms of the width of the square billet

which sections of flexible cable, sometimes of appreciable length, are required to suit the various lengths of billet and tolerances, and it is very difficult to keep them low in reactance and resistance. For this reason it is necessary to dispense with exaggerated facilities for adjustment of the length while the installation is being planned. Moreover, undue adjustment only prolongs the charging time and adversely affects the throughput of the heater unit. To attain optimum efficiency and maximum throughput with reliability it is preferable to aim at keeping the length of the billets as nearly constant as possible. In practice this requirement can often be fulfilled without difficulty, especially in large installations.

A major influence on the economics of such installations is exerted by the arrangement and design of the contacts which transfer the heavy current to the material. By suitably shaping the contacts and choosing the right pressure, as well as by employing an appropriate number of contacts, the heat can be homogeneously distributed over the end of the billet. The Brown Boveri heater units are therefore always equipped with side and end contacts. The waste heat, which does not contribute to the heating of the billet, is dissipated by the coolant.

The loss resistance of a heating installation of this kind comprises the ohmic resistance of the transformer, the leads to the contacts from the secondary terminals of the transformer, and part of the contact

resistance (i.e. between contacts and billet). Since the effective resistance varies with the size of the billets, and the above loss resistances are constant for a certain size of heater unit, the efficiency and with it the power consumption is determined by the dimensions of the billet. Fig. 3 shows the consumption in kWh/t in terms of the width and length of the billet as parameters. The consumption varies between 240 and 400 kWh/t, corresponding to an efficiency of 90–95 %, depending on the cross-section and length of the billet. These figures, however, only possess limited validity, because the length adjustment of the heater also exerts a marked influence on the consumption. They do show, though, that the consumption decreases as the ratio of length to width of the billet grows.

Fig. 4 and 5 illustrate one of the completed installations, consisting of 2 heater units, each with a rating of 1000 kVA. The cross-section of the billets may vary between 40 × 40 and 100 × 100 mm, with billet lengths ranging from 0.7 to 3.1 m. Before each heater is the sensing device which checks the length of every billet before it is introduced into the heater. On the right of the heater is the transformer with the water-cooled tubular conductors carrying the heavy current to the contact heads. The head on the right is kept fixed, while the one on the left is adjustable to suit the different billet lengths. Elevated, behind the heater, is the control desk. This installation has been in service for over two years in a steel-works producing rolled sections, served solely by

these two heater units. With the exception of a small gas-heated furnace for specimen billets there are no other heating facilities. Electric resistance heating has proved ideal in this works, especially on account of its excellent adaptability in service. Despite the continually changing production programme, the installation maintains a high efficiency, as the Table below shows. This is attained by switching the heaters off while the rolling stands are being reset, thereby saving energy.

The layout of a more recent heating installation in which the length can be varied between 1.2 and 2.5 m is shown in Fig. 6. As a result of reducing the adjustment it is possible to keep down the resistance and reactance, so that the efficiency rises to about

Details of steels heated from 20 to 1200 °C in the installation illustrated in Fig. 4 and 5 (with transformer rating 1000 kVA)

Dimensions mm	Heating time s	Energy con- sumption kWh/t	Effi- ciency %	Quality
40 × 40 × 3000	45	258	81	St 37
60 × 60 × 3000	117.5	248	84	St 37
60 × 60 × 1500	76	277	76	St 37
62 × 62 × 2500	48	245	86	high- speed
80 × 80 × 2900	255	308	68	St 37
80 × 80 × 1500	197	320	66	St 37
100 × 100 × 3000	582	353	60	St 37

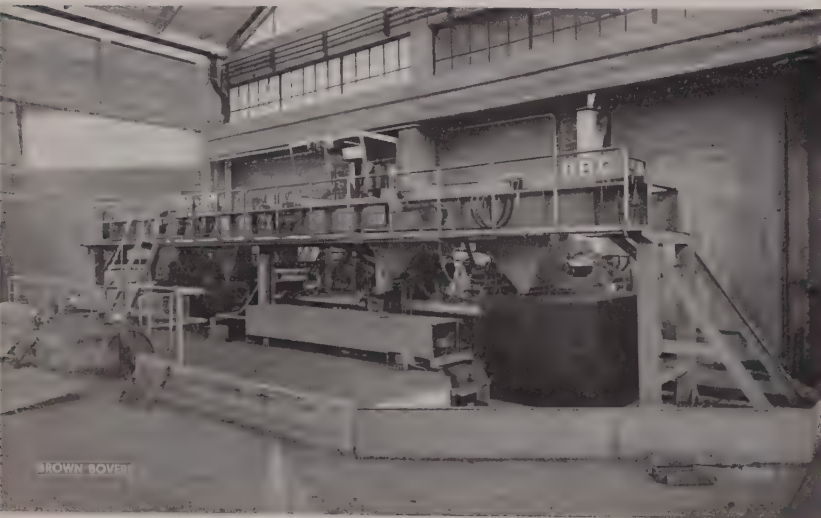


Fig. 4. – Two installations for heating billets by the direct passage of current

Each rated 1000 kVA

Billet cross-section 40–100 mm square, length 0.7–3.1 m

Fig. 5. — Close-up view of part of the billet-heating installation in Fig. 4, showing the billet just before it attains the desired temperature

The picture clearly shows the uniform distribution of the heat through the whole length of the billet

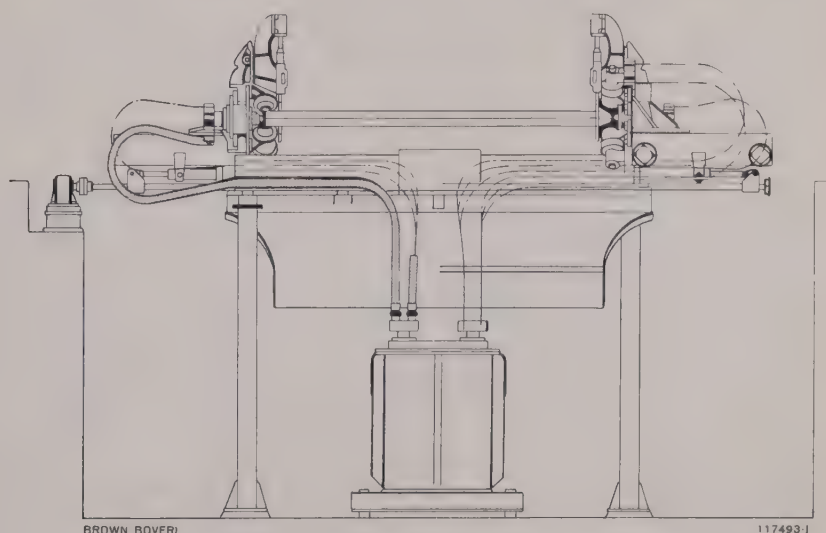
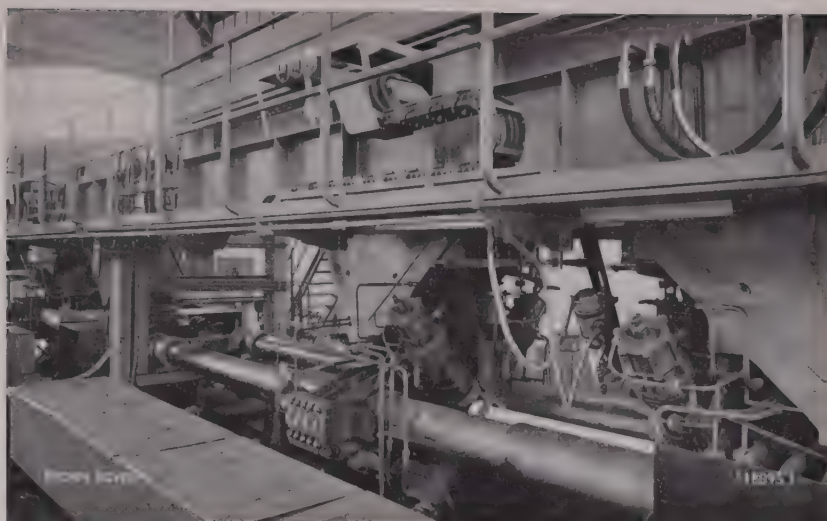


Fig. 6. — Side elevation of a billet-heating installation employing the direct passage of current, suitable for billets ranging from 1.2 to 2.5 m in length

90%. The transformer is mounted in the middle, below the heater, the current being carried to the contacts by flexible water-cooled cables.

Layout of an Automatic Billet-Heating Installation

Fig. 7 depicts schematically the extent and arrangement of a complete installation with four heaters for a total capacity of about 15 t/h, used for heating rectangular billets up to 50 mm square and 2.5 m long.

The main parts of the installation are the input table, the common roller table for charging the

heaters 6a-d and transporting the heated billets on to the first rolling stand. The cold billets are loaded by fork-truck or crane on to the input table, designed as a set of shuffle bars 1, where they are automatically separated. From this sorting device the billets drop singly on to the bed 2 where their length is measured optically or mechanically to check whether it is within the tolerances of the contact setting on the heater. If this condition is not fulfilled, the transfer skid 3 pushes the billet into the reject channel 4, whereupon a fresh billet is automatically delivered. Otherwise the billet is transported by the skid to a point in front of the roller table 5a-d belonging to the particular heater for which the billet was

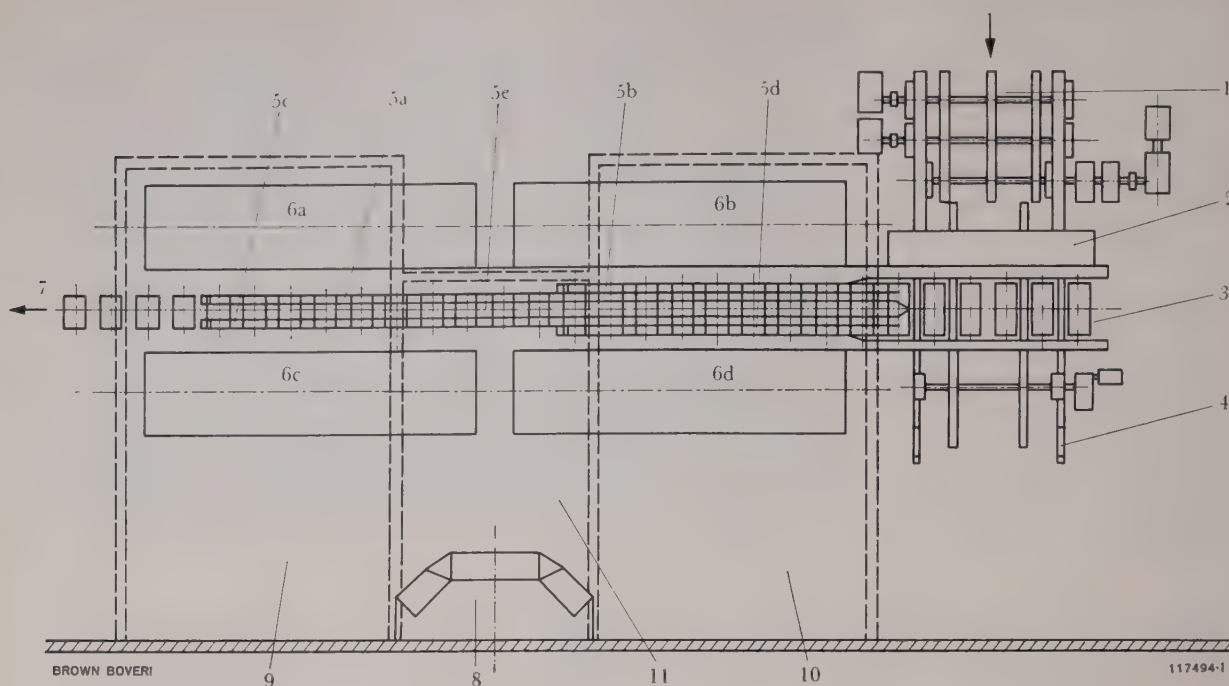


Fig. 7. - Layout plan of an automatically controlled billet-heating installation with four heating units

For notation, see text.

demand, and carried by roller table to the heater. On completion of the heating process the billet is pushed hydraulically into the channel of the middle roller table 5e, which transports it at once to the first rolling stand. Below or next to the heaters is the high-voltage switchgear 9 and 10, as well as the cabinets 11 containing the automatic control gear for the entire installation. To one side and slightly elevated is the control desk 8, from which the operator can supervise and control the whole installation.

In conclusion it may be pointed out once again that electric resistance heating is ideal for elongated metal objects, especially steel billets for rolling, with round or rectangular cross-section. Based on many

years' experience and exhaustive tests, Brown Boveri have successfully solved the problems of switchgear and contacts, and are thus able to fulfil the requirements of the steelworks with their heating units. Owing to the high efficiency with which the electricity is converted into heat, such installations are most economical. Moreover, metallurgical advantages are gained which were unobtainable with any other method of heating used hitherto. These advantages have attracted the attention of the experts to this new method of heating. It is thus well worth considering direct electric resistance heating of billets when planning a new rolling mill.

(KME)

W. ANNEN

TWIN DRIVES IN ROLLING MILLS

621.771.2-83

Drives producing a very high cut-out torque, for use with blooming and slabbing mills, are preferably designed as twin drives, whose practical advantages over mills with a pinion stand also justify their employment when a lower drive torque is required, as for cold-strip mills, for instance. The problems that have to be solved in the control system of a twin drive are explained and the principle of control described.

Problems and Description of the Circuitry

IN THE LAST TEN years increasing use has been made of the twin drive for blooming and slabbing mills, as well as for cold-strip mills. The main reason

for the adoption of the twin drive instead of individual drives is the need for increasingly high powers. Suppose, for instance, the drive of a blooming and slabbing mill requires a cut-out torque of about 400 mt, it would be technically feasible to provide this with a single drive, using a pinion stand, provided the motor was designed as a double-armature machine (Fig. 1 and 2). From economical and technical considerations, single-armature motors can be built for a torque up to 300–350 mt. For double-armature machines the limit is around 600–700 mt. Practice has proved that it is preferable to use twin drives for

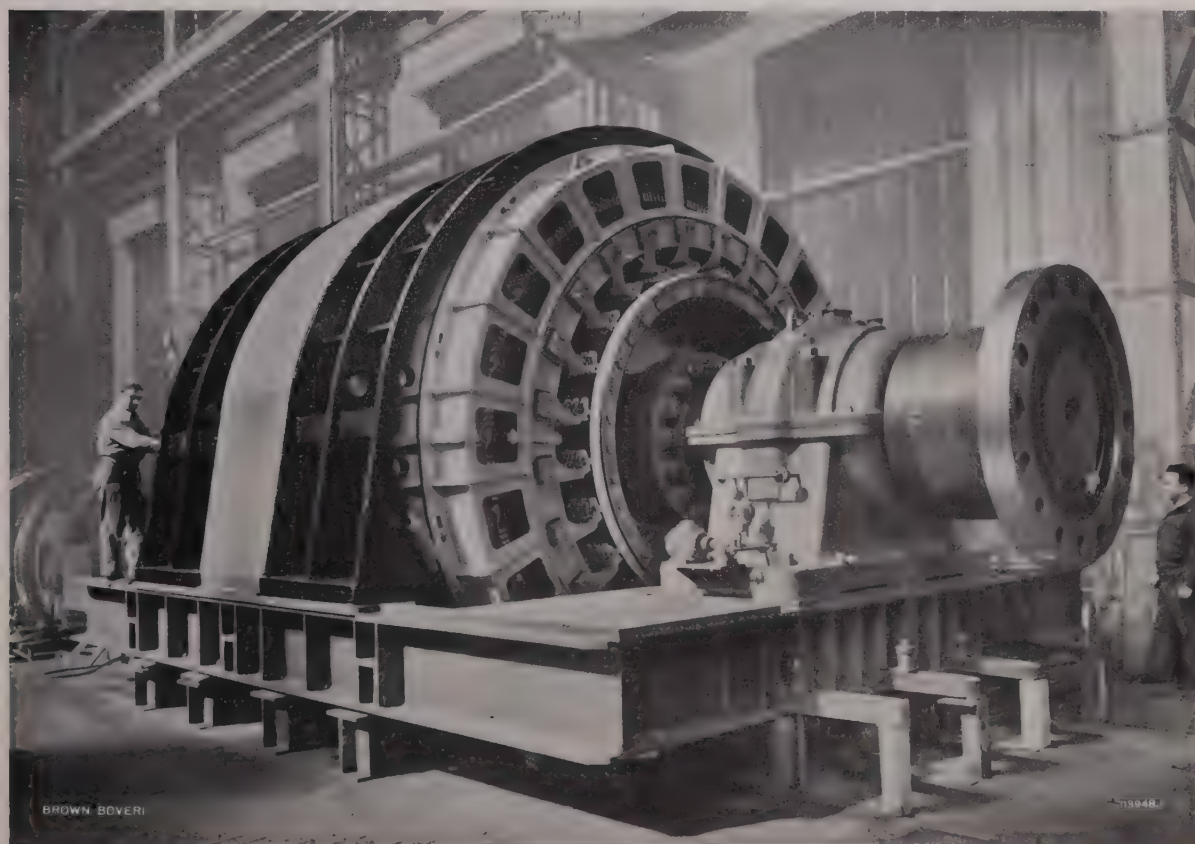


Fig. 1. — One of two double-armature motors for a slabbing mill designed with a twin drive for a cut-out torque of 2×300 mt. Each motor has an effective output of 4500 kW at a speed of 40–80 rev/min.

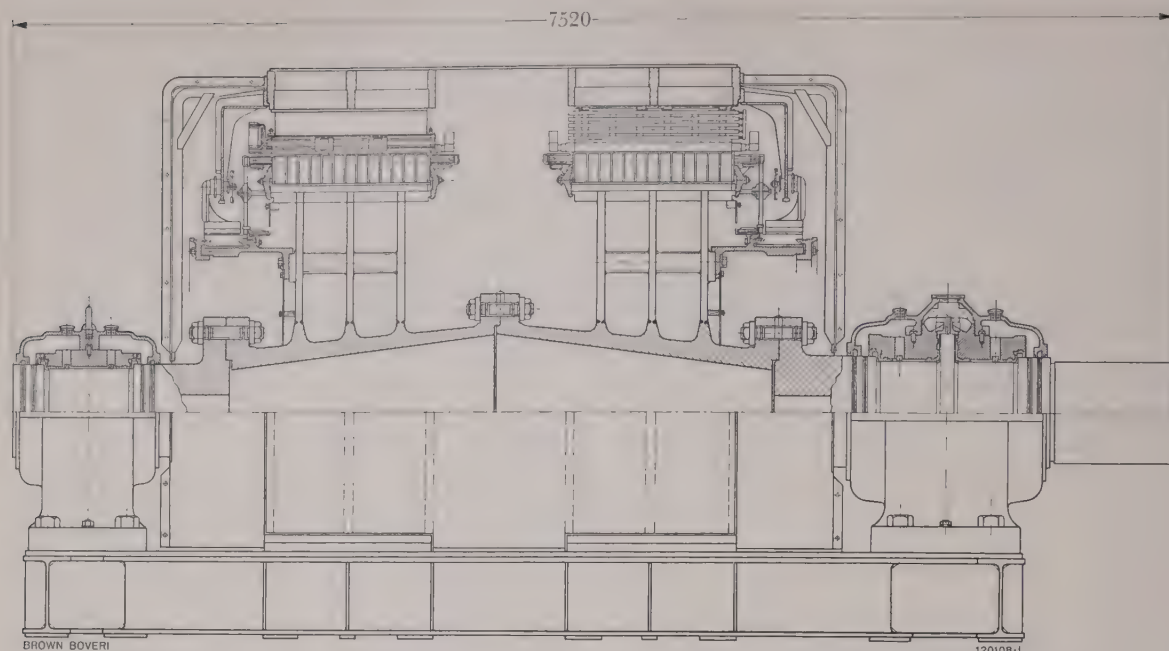


Fig. 2. — Section through a double-armature motor used for driving a reversing mill

reversing stands having a cut-out torque of more than about 300 mt (see Fig. 3 and the coloured plate on the front cover). Thus the limit at which a twin drive should be used instead of an individual drive does not depend solely on the ability to build a suitable machine. The limit is governed far more by mechanical considerations. If the rolling programme stipulates reversal with a very high cut-out torque, say 400 mt, it is quite difficult to design a pinion stand which will withstand this severe stress. But this does not mean that the twin drive is not suitable when smaller powers are required, provided the operating conditions warrant its use.

Apart from the high drive power which makes its use necessary, the twin drive also offers the following advantages over a drive with a pinion stand:

The pinion stand can be eliminated

The power can be split between two motors, which can then be smaller and possess a lower flywheel effect

The rolls can be of different diameters

Ability to roll with forward slip by increasing the speed of the bottom roll prior to ingot entry

The drive spindles can be dimensioned for the cut-out torque of the individual motors

The storage of spare parts is simplified.

As a result of the above advantages twin drives can also be employed for reversing drives requiring lower drive powers.

Generally speaking, the reversing drives of blooming and slabbing mills impose severe requirements, not only on the mechanical equipment, but also on the main and auxiliary electric drives. In the twin drive the electrical system also has to cope with the problems arising out of the elimination of the pinion stand and the associated mechanical linkage between the top and bottom roll. The control system has to be designed in such a manner that it can perform the duties of the pinion stand on the one hand, yet affords an additional improvement compared with the rigid mechanical linkage provided by the ratio of the pinion stand. Characteristic features of reversing drives are the need to maintain reversing times as short as possible, the high peak torques at low working speed during the first pass, and finally the increasing rolling speeds which are being employed, in order to raise the output. The require-

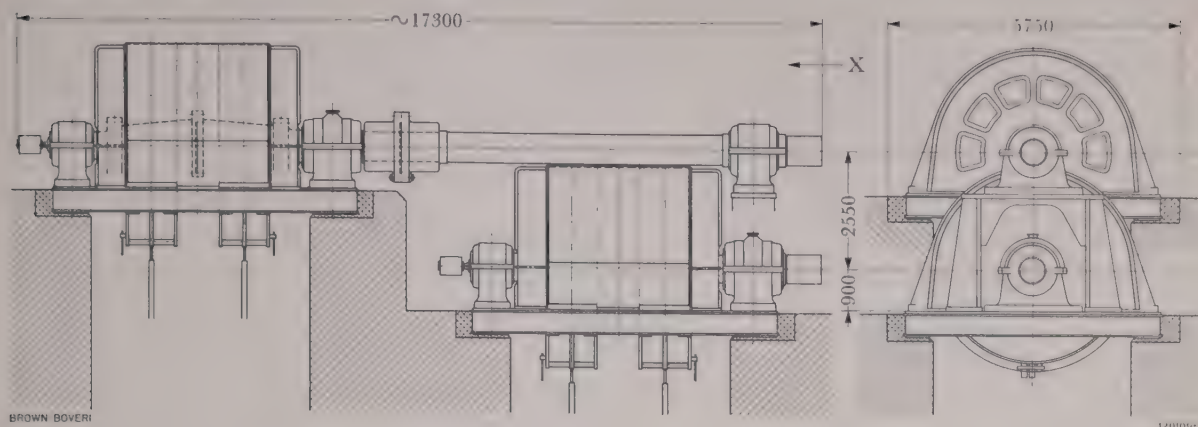


Fig. 3. — Plan and elevation with section in the X direction of the drive of a rolling mill with a cut-out torque of 2×300 mt

ments are best fulfilled by the d.c. motor, preferably fed from mercury-arc converters (mutators). Optimum working speeds in both directions and the inherent limitation of the armature current demand very rapid control of the speed and current of the drive. Furthermore, such mills turn out material which is subsequently processed in billet, rod and wire mills, or in hot or cold-strip mills. Consequently blooming and slabbing mills have to be absolutely reliable, in order to avoid any interruption in the flow of material. This demand for reliability must therefore govern the design of the control system.

The high working speeds of these mills call for rapid run-up, in the range of armature control and in the field-weakening range. Up to the basic speed the excitation of the motor is constant. To overcome the magnetic inertia rapidly in the field-weakening range, the motors are equipped with a field control system with facilities for controlled super-excitation. The resultant rapid adjustment of the field ensures rapid run-up to the maximum speed with field weakening, and electric braking at optimum power in the field-weakening range. This is most important for the reversal time of the drive and in the event of emergency braking.

In a reversing mill with pinion stand the only requirement the motor and control system have to fulfil is that of short reversing time; the transmission of energy to the top and bottom rolls is performed in this case by the pinion stand. When conditions in the roll gap are ideal, i.e. when the

rolls are exactly equal in diameter and friction between the material and the rolls is the same above and below, the distribution of power is certain to be equal owing to the rolls being coupled through the pinion stand. However, quite small deviations by certain factors can lead to undetectable changes in the load distribution, which can adversely affect the rolling process, and which can only be corrected by intervening in the process. Observations have demonstrated that, for part of the time, one of the rolls does not bear fully on the material, with the result that the whole of the energy of the drive motor is transmitted to one roll; consequently the spindles have to be made correspondingly stronger, so as to transmit the full available torque. With the twin drive, where each roll is separately driven by a single- or double-armature motor of its own, the spindles only need to be dimensioned for the maximum torque of one motor.

In the twin drive the motor for each roll is fed separately and has its own control system with rapid response. Instead of a mechanical linkage between the top and bottom rolls as provided by the pinion stand, there is a system of balancing the load distribution by electrical means. It overrides the separate control of the two drive motors and ensures that the peripheral speeds and tangential forces of the top and bottom rolls are evened out, regardless of the difference in their diameters. Fig. 4 shows the speed-power characteristic of an electronic system controlling the balance. The requirements which

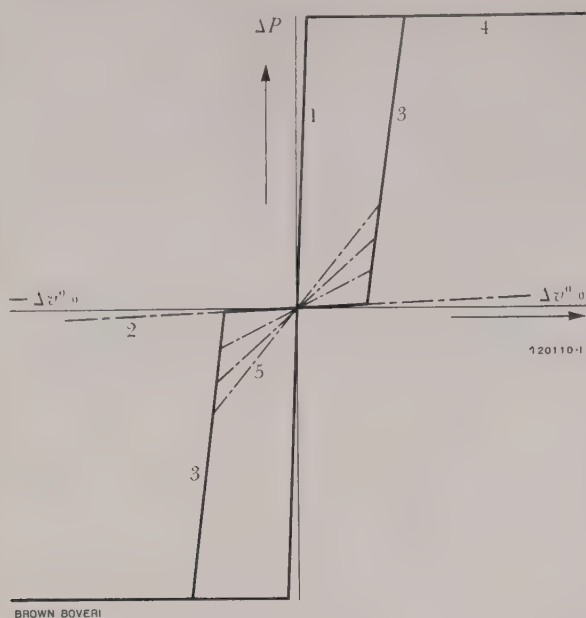


Fig. 4. — Characteristic of the electric linkage between the top and bottom rolls with a twin drive

ΔP = Power difference between top and bottom roll

Δv = Speed difference between the rolls, in % of the momentary speed

1 = Characteristic for rigid speed control, as with pinion stand

2 = Very flexible control of the drives

3 = Limitation characteristic to prevent the motors running apart

4 = Power limitation of the motors

5 = Ratio of power and speed balance adapted to practical conditions for a blooming and slabbing mill

this system has to fulfil on a blooming and slabbing mill are different from those with a cold-strip mill. In the former case the top and bottom rolls are flexibly linked mechanically through the hot thick material; in the cold-strip mill, on the other hand, where the material is relatively thin and less elastic owing to its being cold, the linkage between the rolls is considerably more rigid. When designing the load-balancing system it is therefore essential to aim at an optimum match between the characteristic and the particular working conditions. It is then advantageous if this characteristic can be varied within certain limits.

With the electronic control elements available nowadays it would be quite an easy matter to simulate the mechanical pinion stand by a rigid speed control of the two drives. The system of balancing control, which can then be termed an "electronic pinion stand", has the advantage over the mechanical

pinion stand that it can supervise the load distribution exactly, regardless of the diameters of the rolls. Moreover, the linkage between the individual drives can be made flexible, and thereby make allowance for the requirements of cold-strip mills with regard to good surface finish with minimum wear on the rolls. Experience has shown that, in cold-strip mills, a deviation of $\pm 2\%$ from the working speed may be expected to occur under normal screwdown conditions.

Sudden changes in the friction can cause a roll to slip suddenly; it is therefore important to prevent the motors from running apart at the slightest tendency of the rolls to slip. This running apart is prevented by the broken-line part of the characteristic 3 in Fig. 4. The flexible control of the drives then automatically reverts to a fixed-speed state as soon as one of the rolls exhibits the least tendency to slip. It has been proved in practice that the tolerance in the speed difference, within which slipping does not occur, is large enough to enable an electronic system of balance control to cope with the task. In the case of cold-strip mills the main advantage of the twin drive is that the diameters of the top and bottom rolls may differ from one another. This not only simplifies the storage of spares, but also lowers the cost of dressing.

For blooming and slabbing mills, where the flexible mechanical linkage between the top and bottom rolls is provided by the hot material, the speed programme of the drive should correspond to characteristic 5 in Fig. 4. The mutual dependency between the load balance and the difference in peripheral speed can be set during the commissioning stage to suit the prevailing conditions over quite a wide range. Of course the rolls must be prevented from running apart due to the top or bottom roll sliding. This prevention is performed by the characteristic 3 of the load-balance control.

Fig. 5 illustrates the circuitry of a twin drive. In this example the armature circuit employs the anti-parallel connection, where each motor is fed by its own converter.

The reference value for the rolling speed is provided for both motors by a common element on which the desired speed is set by the operator at the control desk. When controlled automatically, e.g. by

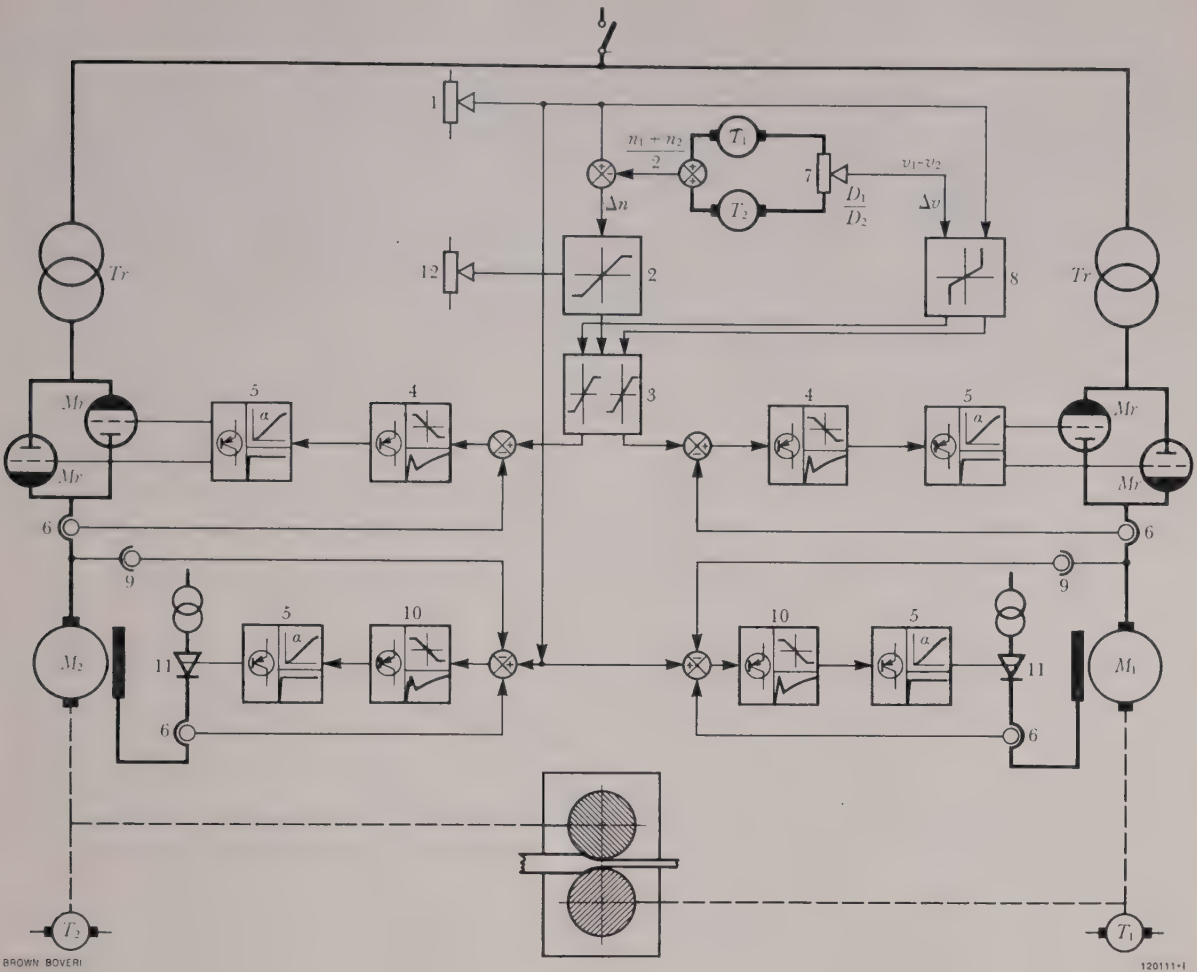


Fig. 5. – Circuit diagram of a twin drive

- M_1, M_2 = Motors

Mr = Mutators (mercury-arc converters)

Tr = Transformers

T_1, T_2 = Tacho-generators

n_1, n_2 = Speeds of rotation

v_1, v_2 = Peripheral speeds

Δn = Speed deviation

Δv = Peripheral speed deviation

D_1, D_2 = Diameters of top and bottom rolls

1 = Setting of desired speed value

2 = Speed controller

3 = Impedance converter

4 = Current controller

5 = Grid control set

6 = Current transformer

7 = Diameter corrector

8 = Load-balance controller

9 = Voltage transformer

10 = Field regulator

11 = Power stage

12 = Setting of controlled compounding

punched cards, the desired speed is fed into the control automatically by a punched-card reader. The voltages of the tacho-generators T_1 and T_2 , proportional to the respective speeds, are added and the mean value obtained $(n_1 + n_2)/2$ is compared with the desired speed value 1. The speed controller 2, acting via the impedance converter 3, produces the reference input for the two motors from the speed

deviation Δn . This ensures that, by means of the closed current-control loops (current controller 4, grid control set 5, mutator Mr and current transformer 6), both drives carry the same current. Provided all mechanical factors, such as friction, flywheel effects, etc., of the top and bottom rolls are equal, and that ideal conditions prevail in the roll gap, the speeds of the two motors will be equal. Furthermore,

the difference $(n_1 - n_2)/2$ between the two tachogenerator voltages is formed. If a speed difference of $\Delta v = v_1 - v_2$ occurs, the balance controller 8 experiences Δv as input, as a result of which it effects a correction in the desired current values of the current-control loops. This ensures that the motors M_1 and M_2 keep to the visualized and permissible speed tolerances, even when the conditions are not ideal.

Any differences in the diameters of the rolls can be taken into account by suitably setting the potentiometer 7. If, for instance, the top roll driven by M_2 tends to slip, the armature current of this motor is reduced by the quick-acting electronic balance control, while that of the motor M_1 is increased by the same amount. When one drive is suddenly relieved of load, the other has to take over temporarily and transmit the full rolling power. By setting a limit to the motor current, a task which only has to be done once, it is possible to ensure that the drive can never be loaded beyond the maximum permissible level. The balance control intervenes with a correction in the opposite sense if the bottom roll exhibits a tendency to slip. By means of the direct check on the speed difference by tachogenerators T_1 and T_2 and the balance controller 8, the drives are prevented from running apart, even when one or the other is loaded to the limit of its range.

For blooming and slabbing mills it is often desirable for the bottom roll to run slightly faster for the first pass, so as to obtain forward slip, thereby preventing the material striking the roller table on emerging from the mill. Immediately after the first pass the speed of the bottom roll can be lowered again, until both rolls are running at the same speed. The speed difference is effected by deliberately falsifying the speed balance—either temporarily or continuously, if desired—by giving the impression that the diameter of the bottom roll is too small. Of course, for forward slip, as well as for the range of tolerances in the limits of characteristic 3 (Fig. 4) it is not the absolute speed difference between the top and bottom rolls which counts, but the percentage difference referred to the momentary speed. Thus the balance characteristic is appropriately influenced by the additional effect of the desired speed value in the

balance controller 8 (Fig. 5). Hence the armature control system with the automatic current balance control largely attends to the maintenance of an even power distribution between the top and bottom rolls. By means of a further control loop the armature voltages of the two motors and, ignoring the voltage drop, their terminal voltages, have to be controlled to the same value. To achieve this the motor voltages measured with the aid of the voltage transformers 9 are compared with the common reference input voltage and the motor fields corrected by the independent control systems (field controller 10 and power stage 12). In the field-weakening range, in which the rated voltages of the motors are equal and regulated to a constant value, the above condition is fulfilled. Thus the speed of the motor driving the roll with the smaller diameter is reduced in proportion to the diameter. With the same armature current for top and bottom roll motors the torques are automatically proportional to the diameter, as stipulated.

In order to fulfil the requirement of equal voltage below the basic speed too, the reference voltage value in the range of armature control is varied in proportion to the rolling speed. By means of an excitation

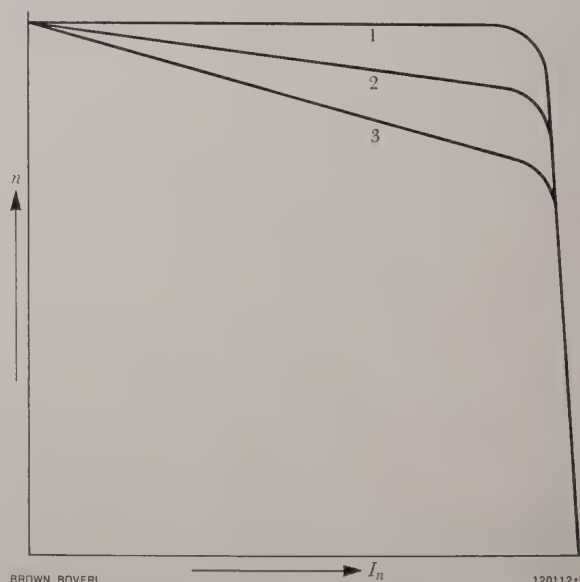


Fig. 6. — External characteristic of the controlled d.c. motor

n = Speed in rev/min

I_n = Load current in A

1 = With rigid speed control

2, 3 = Speed curve with variable controlled compounding



Fig. 7. — Tier from a switchboard containing control gear for a twin drive in a rolling mill

The withdrawn sub-assembly, an element of the Brown Boveri electronic system, is used to split up the control circuits manually and check them one at a time.

control system acting in parallel with the voltage control the excitation current is not only limited to a permissible maximum value but, allowing for the diameter of the rolls, is used to control the field at standstill.

For multi-stand mills, where the material may be in more than one stand at the same time, such as in a tandem mill, it is desirable for the load-speed characteristic to be variable to suit the particular conditions (Fig. 6). This characteristic is set to suit the rolling conditions by means of element 12. This controlled compounding with the twin drive is superposed on the load-balance control which,

though the motor characteristic may be dependent on the load, as described above, ensures that the load is evenly distributed in accordance with the balance characteristic.

All the control circuits required for the twin drive are composed of elements of the Brown Boveri electronic system (see Fig. 7), and they can be divided into a number of similar basic elements. The steelworks engineer can thus be given a circuit diagram which is easy to read, and from which the circuits themselves can easily be checked.

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CONTINUOUS ROLLING MILLS

621.771.2

The technical problems associated with continuous rolling mills, and the resultant requirements which the electrical equipment has to fulfil are described at the beginning of this article. The unit connection, where each motor is individually fed from its own static converter, is the best arrangement for such drives, owing to its excellent control properties. The article concludes with a reference to the conditions that have to be fulfilled by the associated auxiliaries and the behaviour of the drives when a brief mains failure occurs.

IN CONTINUOUS mills the material, supplied by the blooming mill or coming direct from a continuous casting plant, is rolled down to normal commercial dimensions in a succession of passes through several rolling stands. Whether the final product be wire, rod, strip or sections, it always has to comply with very strict requirements as regards dimensional accuracy. But, at the same time, the mill must be able to achieve a high output with lowest possible production costs.

A true-to-gauge final product is obtained by rolling free from tension and with a constant roll gap. In older installations this condition was fulfilled by open-type rolling trains for single-strand operation. Between the individual stands, which were usually mechanically coupled and driven by a single motor, the material formed a large loop. Of course the roll gap of the succeeding stands had to be very exactly matched, thereby impairing the overall flexibility. The maximum rolling speed was limited by the fact that the material had to change direction so often on its way through the mill.

The output of the mill depends directly on the rolling speed and the overall utilization factor. Modern, continuous mills, in which the material runs straight through a succession of stands built in one line, operate at speeds up to 40 m/s. The distance

between separate stands is kept small, not only to save space, but also to reduce the distance for which the flexible material has to be handled.

When several strands are rolled simultaneously, the overall utilization factor is also improved. The expansion of the stands and the sag of the rolls varies with the number of strands running through. Thus, with multi-strand rolling, it is no longer possible to guarantee the constancy of the roll gap; but, as mentioned earlier, it is a factor which governs the dimensional accuracy of the finished product.

In order that the entry of a strand into a rolling stand may not disturb the speed coordination of the various stands, owing to the sudden increase in load, the drive motors have to be equipped with a first-class speed control system.

In modern continuous mills the roughing and intermediate trains are built for multi-strand operation, while the adjoining finishing train is only single-strand. Between the stands of the finishing train looping devices are arranged to ensure that rolling is free from tension under all conditions. In this way irregularities in the gauge of the material, caused by the displacement of the rolls in the roughing and intermediate trains, can be reduced to a permissible minimum. Controlling the loops at the high rolling speeds also imposes stringent requirements on the control gear of the drives for the finishing train.

In conformity with the wide range of products which can be rolled in one mill, facilities must be provided to allow the speeds of the individual stands to be flexibly adapted to the rolling programme, thus enabling the mill to be run economically with each programme. This flexibility is attained with separately driven stands with independently variable speed ranges. Owing to its excellent control properties the

d.c. motor is employed almost exclusively for the main drives. In view of the immediate response and easy control of mercury-arc converters, the unit connection of motor and converter is the ideal arrangement for such drives.

Rational rolling, i.e. high output, can only be achieved when all the equipment associated with a rolling mill fulfils the resultant requirements. Since the auxiliary drives also have to perform some very important duties, close attention has also to be paid to the electrical equipment of these drives. Here too there is a general tendency for the rotating converter to be superseded by the static converter.

Feeding the Main Drives

Continuously running drives can be fed either by the unit connection, or from busbars, the main differences between which are as follows (Fig. 1): In the unit connection each motor is fed by its own converter as an autonomous unit, in contrast to groups of motors being fed in parallel from a set of busbars.

Unit Connection

This method of connection affords quite a wide choice for the speed ranges of the individual motors. It is also possible to run up or stop the motors separately. For these reasons, but also on account of the technical advantages from the control aspect, most main drives for continuous mills are nowadays

supplied in unit connection. The principle of the control system is illustrated in Fig. 2. It comprises three independent control loops, i.e. for speed, voltage, and for limitation of the current. The speeds of the motors can be set to the desired value by means of the reference potentiometers (Fig. 3). These are motor-driven and can be operated remotely from the control desk, where the setting is also indicated with an accuracy of 0.1 %.

The individual reference potentiometers can also be jointly varied by follow-up control; in this case, when one setting is changed, the settings of all drives following it or preceding it, depending on the principle of control employed for the particular train, are also varied. In this way the coordination between the speeds of successive stands is maintained.

When the programme is changed, the machinist can set the speeds of individual stands exactly to the values required for that programme. Owing to the high speeds of finishing trains of modern mills, it is no longer possible to make subsequent corrections to the speed setting in a reasonable time. Since the stands of the finishing train automatically adjust themselves to rolling without tension, via the loopers and the follow-up control of the stands, they are run to produce tension at the start. In order to be able to cope with the size of the loops at high rolling speeds, the speed control of each drive must have an extremely rapid response. As mentioned at the beginning of the article, the multi-strand roughing and intermediate trains also require a high standard

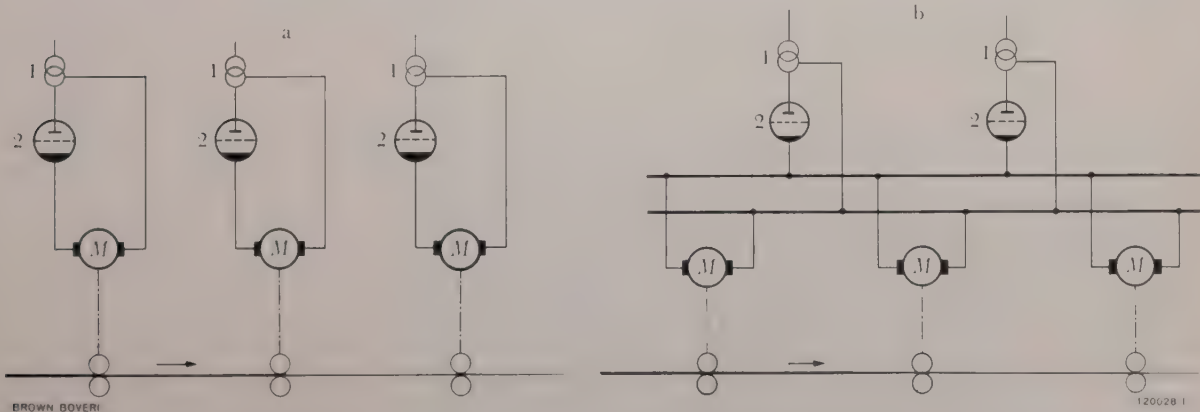


Fig. 1. - Connections employed for continuously running drives

a: Unit connection b: Supply from busbars 1 = Transformers 2 = Mercury-arc converters M = Motors

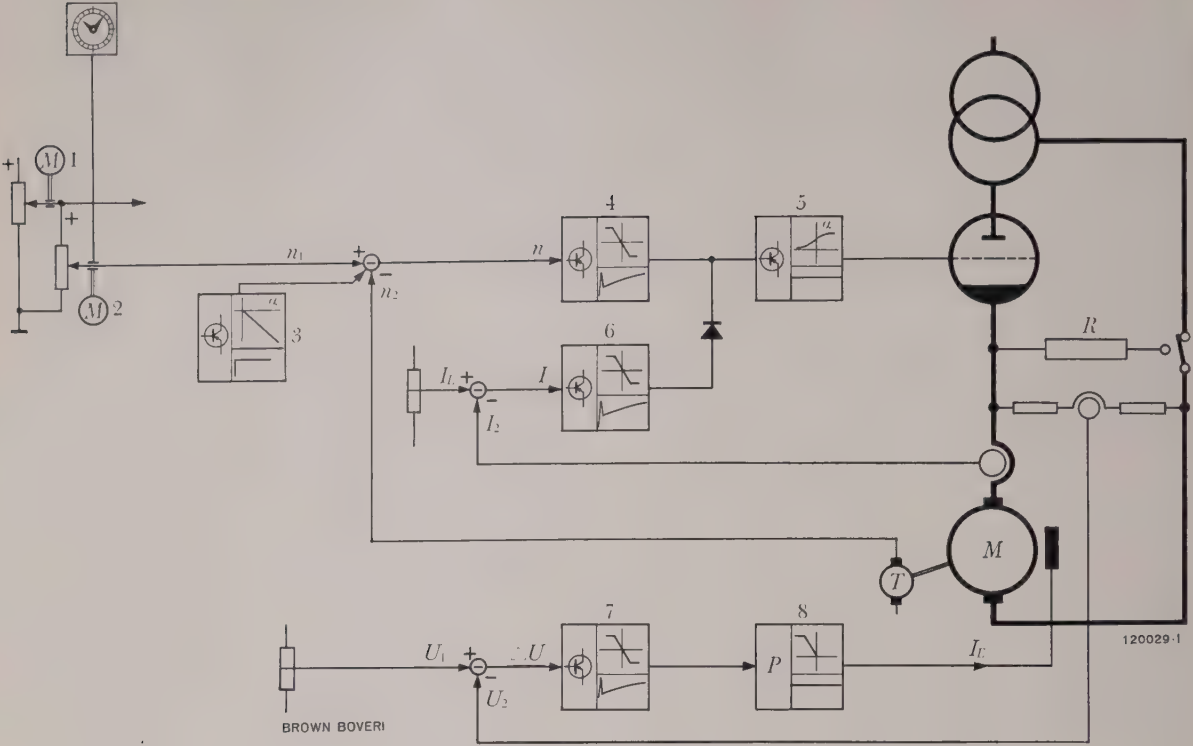


Fig. 2. - Block diagram of the unit connection

a	b
c	

- a = Basic element
- b = Simplified static characteristic
- c = Simplified transfer function
- 1 = Starting potentiometer
- 2 = Reference potentiometer with remote indicator
- 3 = Loop-measuring device

- 4 = Speed controller
- 5 = Grid control set
- 6 = Current controller
- 7 = Voltage regulator
- 8 = Field supply unit
- M = Motor
- T = Tacho-generator

- R = Braking resistor
- n_1, U_1 = Desired values
- I_L = Limit value
- n_2, I_2, U_2 = Actual values
- Δn = Speed deviation
- I_E = Field current
- P = Power stage

of speed control, in order to correct the dynamic drop in speed caused by the entry of a strand. This avoids any adverse effect on the other strands. The

speed is corrected by varying the firing point of the converters and thus varying the motor voltage. The speed is measured with a high-grade tachogenerator

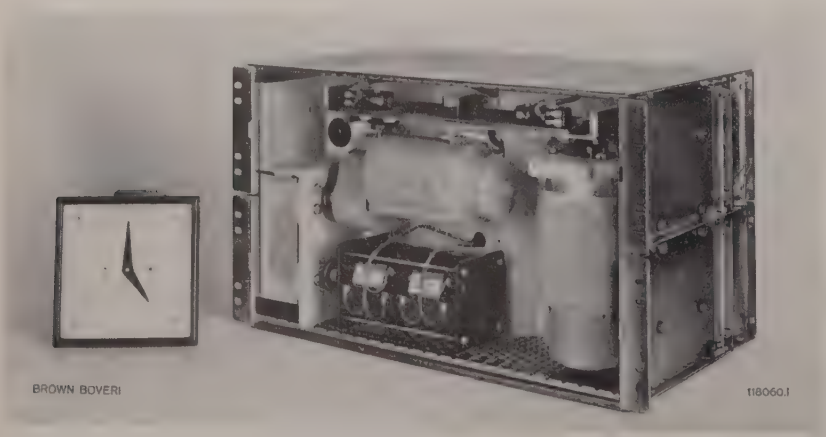


Fig. 3. - Reference potentiometer for desired speed

With remote indication, accuracy of setting within $\pm 0.1\%$

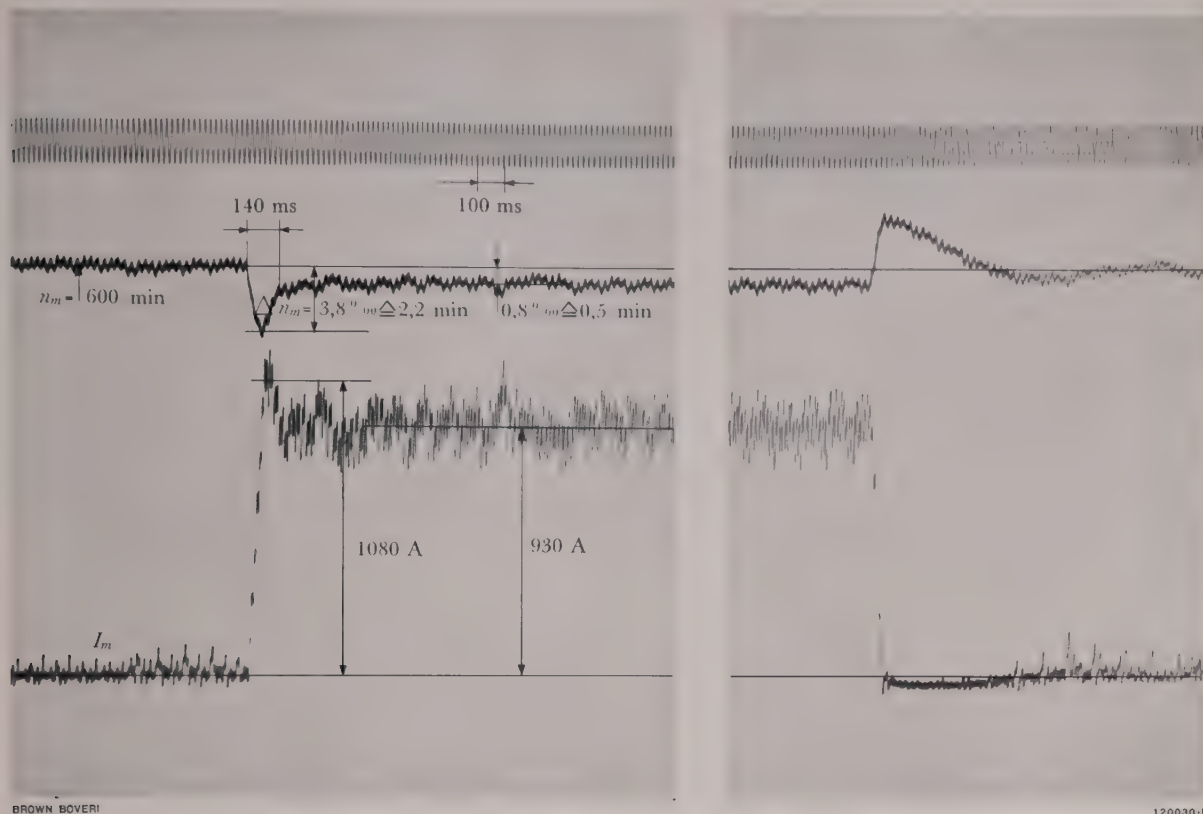


Fig. 4. — Unit-connected motor, application and removal of the load

n_m = Motor speed (in rev/min) I_m = Motor current

and compared with the desired value. The amplified deviation is used to control the converters through their grid control sets. Increasing the converter voltage raises the armature current and thus accelerates the motor to the required speed. Since the speed control loop does not contain any elements involving any time-lags worth mentioning, the excellent quality of the control, as expressed by its immediate response, is evident.

The oscillogram in Fig. 4 shows the dynamic and static behaviour of the motor driving a rolling mill during the sudden application and removal of a load. The motor is rotating at its basic speed, the load current corresponds to the rated value. The steady-state speed drop $\Delta n_m = 0.08\%$; the response or quality of control, as expressed by the product of the above speed drop and the settling time, works out to about 0.04% s.

The angular lag of the motor shaft with respect to uniform rotation, caused by the temporary speed

drop due to rated load surge, is only $1-2^\circ$. Considering, for example, that for four-strand rolling, the entry of one strand only amounts to $\frac{1}{4}$ of the rated load, and also remembering that on roughing and intermediate trains, the motor speed is stepped down to the rolls through gearing, it will be obvious that the temporary difference in length suffered by the strands actually running through is only of the order of one millimetre.

The electrical simulation of the loop is superposed on the speed control, the loop control system having an integral action. The loop is measured by the device described in the article beginning on page 663 and the speed of the next stand varied so as to maintain constant loop height.

The extension of the speed range beyond the basic speed is effected by field weakening, performed by the voltage control system. Under the influence of the speed control the motor voltage is temporarily increased. By field weakening, the voltage control

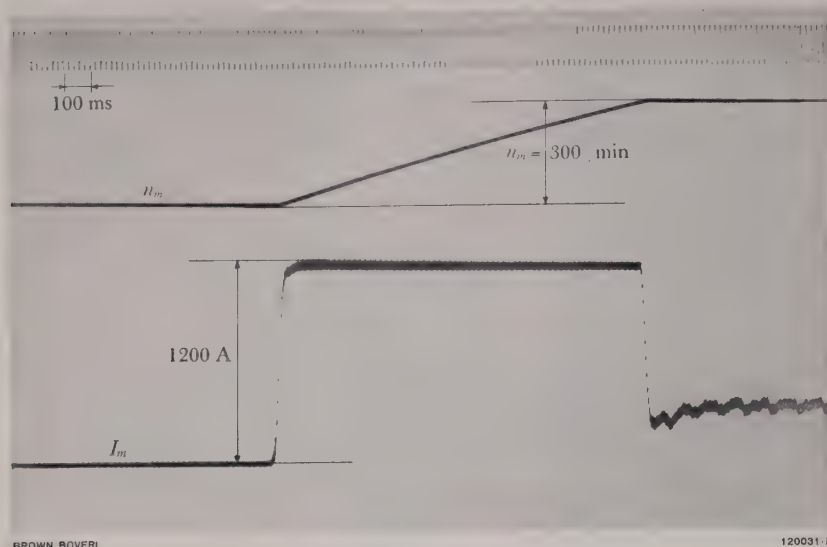


Fig. 5. — Unit-connected motor with parallel limitation of the current

n_m = Motor speed (in rev/min)
 I_m = Motor current

brings the motor voltage up to its rated value, thereby raising the speed to the set desired value. In order to assure the necessary galvanic separation between the main and control circuits, the motor voltage is measured through d.c. current transformers. The motor fields are preferably fed from static elements, such as magnetic amplifiers. Under extreme conditions, e.g. when the loop grows unduly rapidly or when cold material enters the roll gap, the demands made on the speed control circuit may

be so severe that the current exceeds the permissible value for a short time. By means of a control circuit parallel to the speed control, the motor current is limited to the maximum permissible level, thus preventing the switch from tripping. Under such conditions, though, reliable rolling is no longer assured, as the speeds of the motors are not under complete control. The oscillogram in Fig. 5 shows the motor current running up to the limit.

For certain kinds of drives, e.g. for edgers and pinch rolls, it is desirable to have a "soft" characteristic; this can be attained by cascaded speed and current control loops, the "soft" characteristic of the motor being optimally adapted to the conditions by a special circuit (Fig. 6).

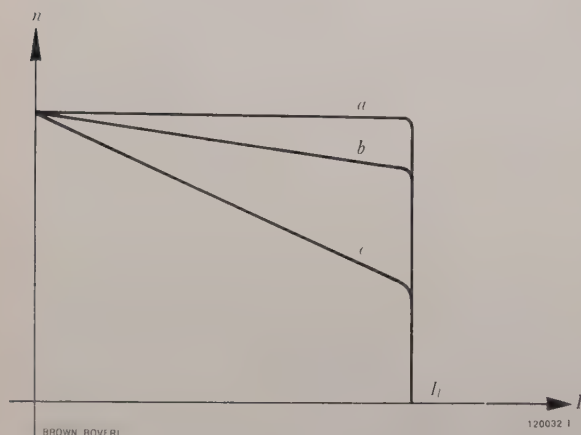


Fig. 6. — Motor characteristics

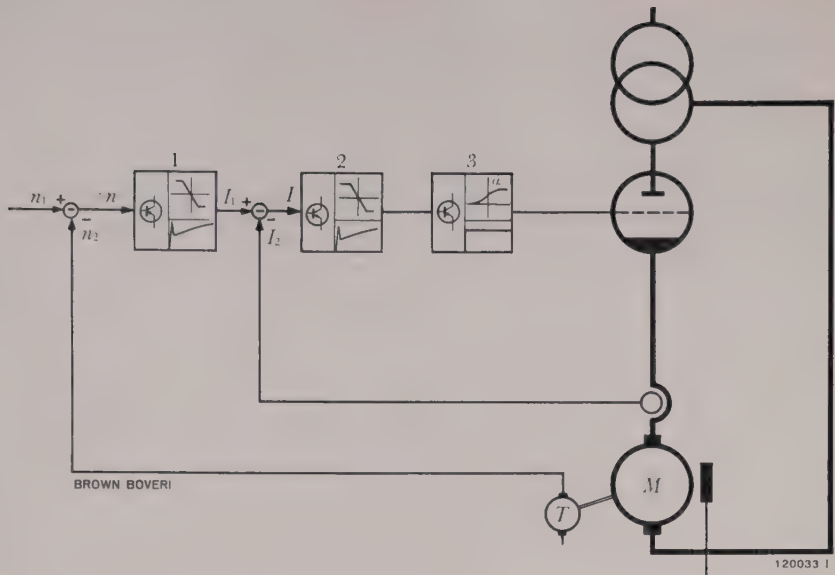
n = Motor speed
 I = Motor current
 I_L = Set limit current
 a = Hard characteristic, with parallel current limitation
 b, c = Soft characteristics, with cascade control; slope of speed drop can be set to suit requirements.

In contrast to parallel current limitation (Fig. 2), in which either the speed or the current control loop is in action, with the cascade control the speed loop overrides the inherently closed current control loop. In this case the amplified speed deviation provides the desired value for the current control. Fig. 7 shows the block diagram of a speed-current cascade, the actual curves of current and speed when a motor of this kind of drive is subjected to loading being illustrated by the oscillogram in Fig. 9.

In an emergency the entire train may have to be stopped in as short a time as possible. For such emergency braking operations the desired speed is reduced to zero at once. At the same time the motors are disconnected from their supply units, switched over

Fig. 7. — Block diagram of a cascaded speed-current control system

- 1 = Speed controller
- 2 = Current controller
- 3 = Grid control set
- M = Motor
- T = Tacho-generator



to braking resistors, the voltage control regulating the motors to their rated voltage down to the basic speed. The braking resistors are dimensioned so that emergency braking takes place with 1.5–2 times the rated current, i.e. braking is effected by field weakening with 1.5 to 2 times the rated power.

Fig. 8 shows a standard type of control cabinet housing the Brown Boveri electronic equipment for the entire control system of a unit-connected drive. Mounted in the hinged frame are the tiers containing the plug-in printed-circuit modules, while in the bottom of the cabinet are the magnetic amplifiers feeding the field. The protective and interlocking elements are attached to the rear of the cabinet.

Busbar Supply

The use of the busbar system of supply is usually only justifiable for motors of low rating. If several high-powered motors are fed from busbars, the possible short-circuit power becomes undesirably high.

In order to keep the supply voltage for the motors constant, despite mains voltage fluctuation, the busbar voltage has to be regulated. Without this voltage regulation the motors would have to be dimensioned for higher powers because they must be able to produce the full desired power at the minimum anticipated voltage. Furthermore, at the maximum anti-

cipated supply voltage, the motor speed would have to be capable of reduction down to the basic value.

If several static converters are supplying a busbar system, it is convenient to form two separate supply

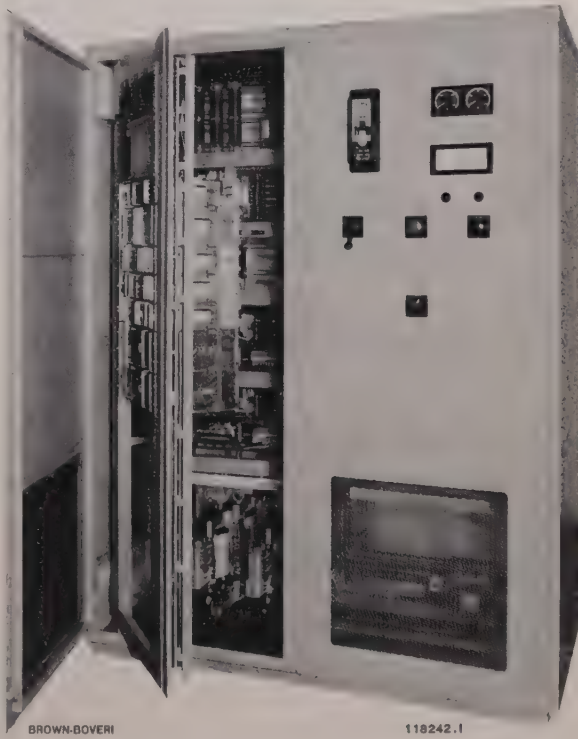


Fig. 8. — Cabinet with hinged frames (left-hand half) containing all the control and field supply equipment for a unit-connected or busbar-fed drive.

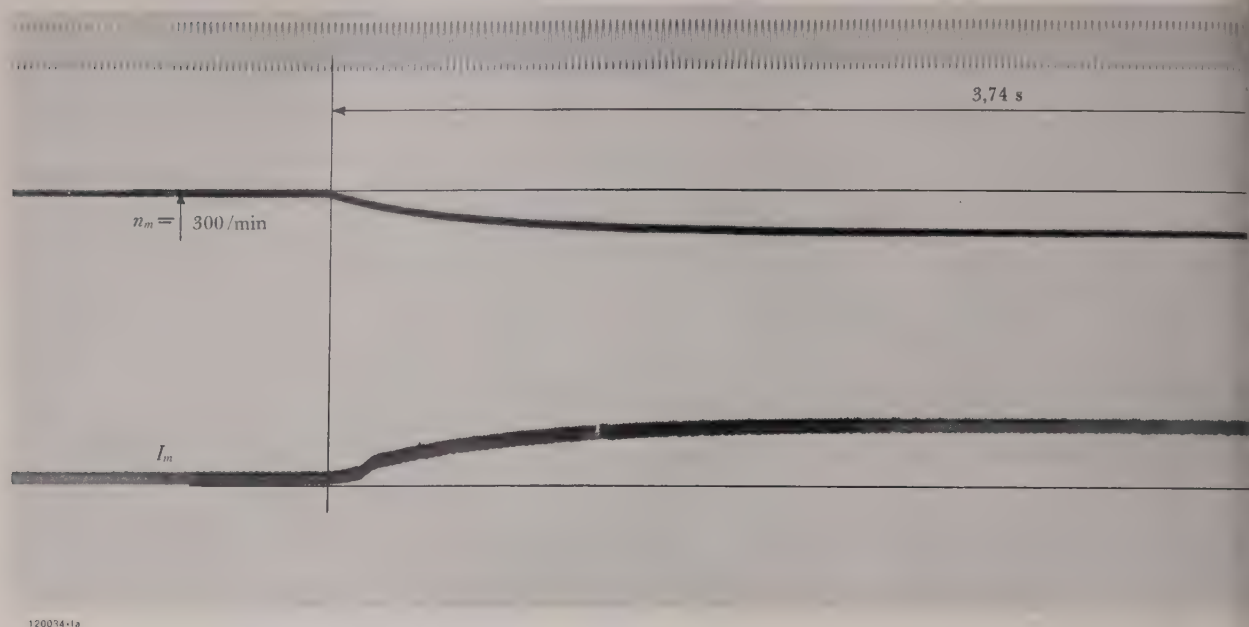


Fig. 9. – Load oscillogram of a motor controlled by a speed-current cascade

n_m = Motor speed (in rev/min) I_m = Motor current

units (Fig. 10). Each unit comprises a transformer and one, two or more converters. Even with a control section common to both units, i.e. reference voltage potentiometer, controller and grid control sets, there

is no guarantee that the current would be uniformly distributed, because the distribution is governed by the impedance of the feeding elements. If a good load distribution is desired under all circumstances, it is

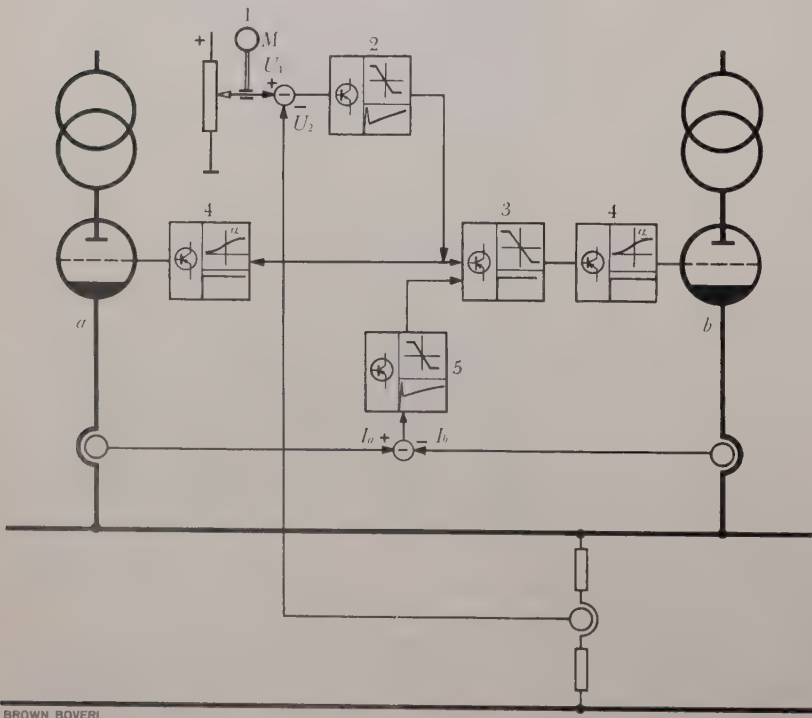
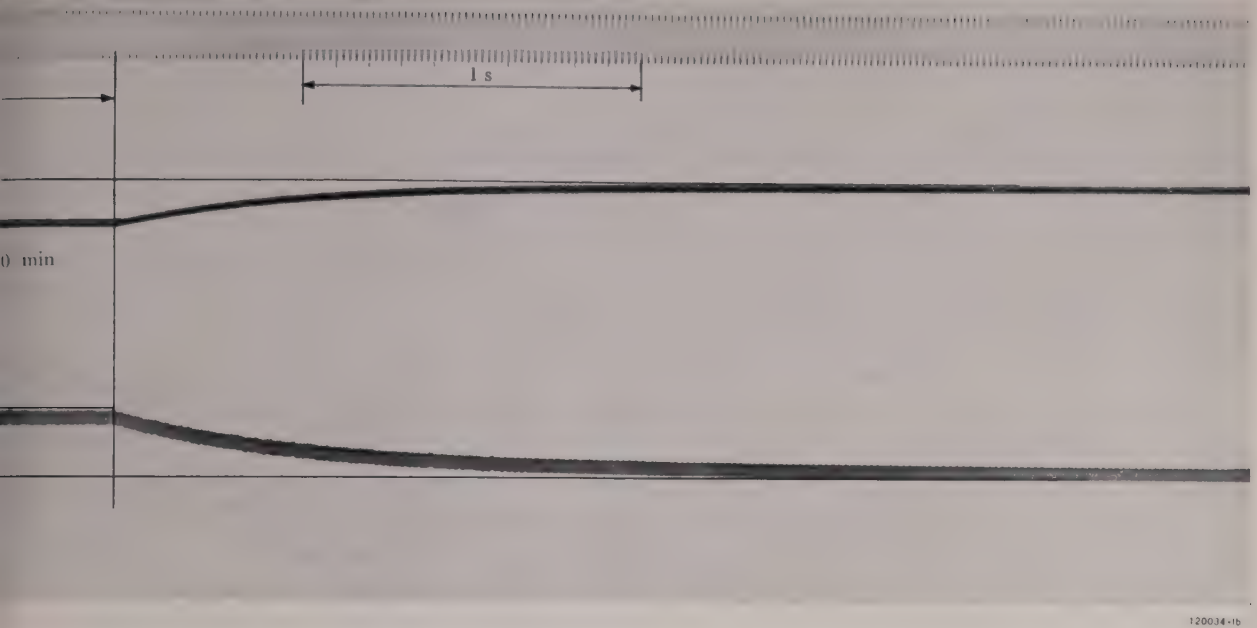


Fig. 10. – Voltage regulation with load balancing of a busbar supply system

- 1 = Starting potentiometer driven by motor M
- 2 = Voltage regulator
- 3 = Proportional-action amplifier
- 4 = Grid control set
- 5 = Current balancing device
- a, b = Feed units
- I_a, I_b = Currents of the feed units
- U_1 = Desired voltage value
- U_2 = Actual voltage value



necessary to resort to a system to control the load balance. Here the currents of the feed units are measured, the difference being utilized to correct one of the two converters until the balance is restored.

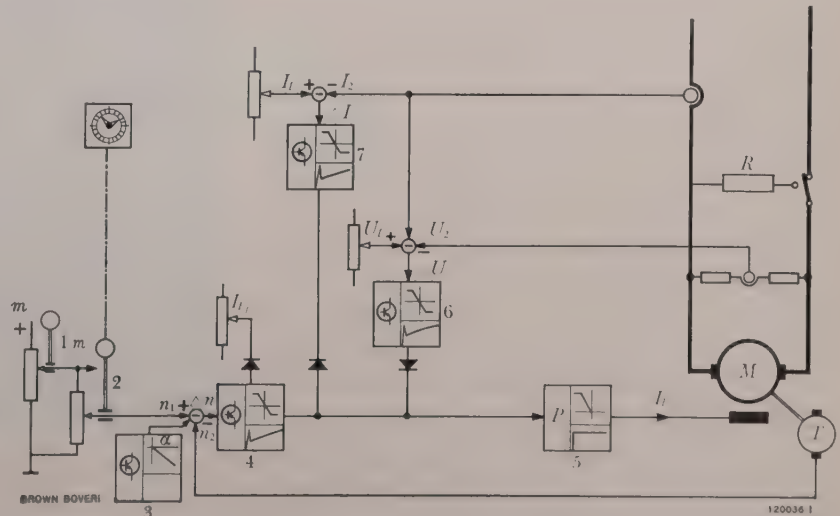
The speed control of busbar-fed motors is no longer effected through the armature but through the field. In contrast to the unit connection, where a speed deviation produces, via the converter, an increase in the voltage at the motor terminals, with field control by field weakening the e.m.f. of the motor is lowered. On account of the time constant of the field, the speed is controlled much more slowly than in the unit

connection unless of course special precautions are taken. When the field is fed direct via thyristors (Fig. 11) or controlled silicon rectifiers, with suitable super-excitation, quite good control times are obtained. For drives whose demands on the response are less severe the field can be fed via magnetic amplifiers.

The necessary range of field weakening for busbar-fed drives is normally of the order of 1 : 3. Provided the torque, reduced by field weakening, is still adequate for rolling, this range can be extended. For the same reasons as given above in reference to the unit connection, the drives also require a means of

Fig. 11. — Block diagram of a busbar-fed drive

- 1 = Starting potentiometer driven by motor *m*
 - 2 = Reference potentiometer with remote indicator
 - 3 = Loop-measuring device
 - 4 = Speed controller
 - 5 = Field supply unit
 - 6 = Voltage limiter
 - 7 = Current controller
- R* = Braking resistor
M = Main motor
T = Tacho-generator
P = Power stage
 n_1 = Desired speed
 I_L, U_L, I_{EL} = Limiting values
 n_2, U_2, I_2 = Actual values
 I_E = Excitation current



limiting the current. This applies particularly when the speed control is employed with overriding loop control.

Since the motors have a long run-out time, the difference between the desired and actual values of the speed grows steadily during run-down, thereby increasing the field. Thus, unless special measures were taken, the motor voltage could rise to three times its rated value if the field-weakening range is 1 : 3. By means of the circuit limiting the voltage, in parallel with the speed control circuit, the field is prevented from increasing when the voltage reaches the set limit; this likewise prevents the voltage from rising any further. An influence varying with the armature current is also introduced into the voltage limiting system, to prevent balancing currents flowing between the motors.

Auxiliary Drives

Apart from the main drives, a number of auxiliaries are also engaged in ensuring that the operation of the rolling mill is as rational as possible. All auxiliary drives which are running with the mill, such as the shears, pinch rolls, coilers, and so on, have to follow the rolling speed; hence their speeds have to be controlled accordingly. Such drives, whose ratings may range from about 20 to 60 kW, have been fed hitherto from Ward-Leonard sets. But for some time now there has been a tendency to employ static converters, such as magnetic amplifiers, for feeding the armature; nowadays Brown Boveri are also building semiconductor thyatron units for the same task. Thus static converters can now be used to feed Garrett coilers, which have to be accelerated and braked in operation.

Particularly severe are the conditions laid down for the flying shears, which have to be accelerated in an extremely short space of time and then braked. Mutators and silicon thyratrons are therefore ideal for feeding such drives.

Another important auxiliary is the cooling bed [1], the task of which is to cut down the rolled material to equal lengths, to brake it and transport it slowly across the bed. The speed of this transverse motion is made such that the rods have cooled down sufficiently on reaching the run-out table and are

thus ready for subsequent treatment, such as cutting down to commercial lengths, twisting and bundling. The main stipulations made regarding the cooling bed and its control system are: the entire operation of the cooling bed must be performed automatically, maintaining the length and position of the rods accurately, regardless of the rolling speed.

Using the building blocks of the Brown Boveri electronic system, cooling-bed control system have been devised which allow the above requirements to be fulfilled with remarkable accuracy. Until now it was only possible to measure the length of a rod when it lay, cut, on the cooling bed. The automatic means of measuring the length allows the exact length of the rod to be determined on the control pulpit, regardless of the forward slip.

The control of the cooling bed and several other auxiliary drives is effected as a function of the position of the material on its way through the rolling mill. The position of the rod is determined with respect to time by a photo-cell (Fig. 12) forming part of a control system which has rendered excellent service in a number of rolling mills [2].

Effect of Brief Mains Failures on Drives

In the event of a brief failure or temporary drop in mains voltage, the contactors might drop out, causing the motor to stop. Rolling might therefore

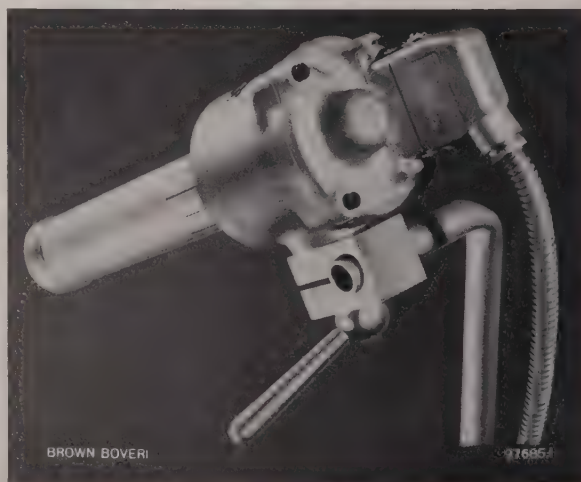


Fig. 12. — Photo-electric detector responding to infra-red radiation, for use in steelworks and rolling mills

experience a long interruption, especially when the material is passing through several stands at the same time. This leads to a tedious process of cleaning out the entire train.

When the control contactors, motor fields and the complete control system are fed from a rotating converter with a flywheel, which supplies the energy for the auxiliaries during a mains interruption, it is possible to bridge over such brief voltage drops. The speed of the rolling-stand motors drops in accordance with their momentary load and their time constant when the mains voltage fails. In the event of failure of the supply voltage—lasting about 300 ms, corresponding roughly to the time taken for rapid auto-reclosure—the motor speed, and with it the e.m.f., assuming constant field, drops by 5 to 30 % at rated load, depending on the state of field weakening. Since the mercury-arc converters would immediately produce full output when the mains voltage returned, it is necessary to lower the desired value for the speed in the event of mains failure, and the desired voltage for busbar-fed drives. The rate at which it is reduced should be at least as high as the maximum drop in speed. When the mains voltage is restored the desired

values for speed and voltage must be steadily raised back to their ultimate value, so that the motors run up under control without any overcurrent. This variation of the reference values is performed by an electronically controlled unit. Its asymmetrically functioning control section lowers the desired voltage quickly when the mains fails, and raises it slowly when the mains voltage is restored.

It is obvious that proper rolling will not be possible during the short time that the supply voltage is missing, because the motors are no longer electrically controlled. By supplying all vital elements of the installation from a converter set equipped with a flywheel, however, it is possible to prevent a stoppage of the entire rolling mill.

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COLD-STRIP MILLS

621.771.274

Following a brief summary of the most important kinds of cold-strip rolling mills and the products they turn out, the article describes the requirements that the electrical equipment has to fulfil. For driving the rolling mill and the coilers it is common practice to use d.c. motors fed either from Ward-Leonard converters or from mercury-arc converters in either the single or two-converter connection. The strict conditions laid down regarding the quality and dimensional accuracy of the final products pose some interesting problems for the control system of the roll and coiler motors, some details of which are given, with reference to the various feed methods. It is constructed on the building-block principle from elements of the Brown Boveri electronic system.

Feed and Control of the Drive Machines

THE stipulations made regarding the quality of the material produced by cold-strip mills are being constantly increased, in order to promote the rationalization of the consuming industries and improve their capacity. These quality requirements, which concern primarily the mechanical and technological properties, the surface finish and the maintenance of minimum thickness tolerances, demand an equally careful treatment of the problems associated with the electric drives and their control, as will be described later.

Cold-strip mills are usually employed for the production of plates, sheets or strips, sometimes with intermediate heat treatment, from steel, non-ferrous and light metals, and even gold and silver. Aluminium foil can be rolled to a minimum thickness of about 3μ . The Table below lists approximate figures for the main products rolled in cold-strip mills.

The strip speeds vary between the following limits, depending on the material being rolled and its thickness:

Reducing	appr. 30–1800 m/min
Skin-pass rolling	appr. 300–1200 m/min

The range of motor outputs required for driving the rolling stands, the coilers and the tension rolls is very wide:

Rolling stand	appr. 100–4000 kW
Coilers	appr. 5–2000 kW
Tension rolls	appr. 50– 300 kW

The commonest types of stands are the two-high stand, the four-high stand with work rolls 120 to 600 mm in diameter and back-up rolls 250 to 1600 mm in diameter, as well as the Sendzimir mill whose work rolls range from 30 to 100 mm in diameter. The drive may be either through a pinion stand, or a twin drive with the top and bottom rolls driven separately. The latter is usually only considered for very high-powered drives, for purely economic reasons.

The design of cold-strip mills is subject to considerable variation. The simplest form of mill, now seldom used for sheet metal, does not possess any coilers but merely a roller table on either side of the rolling stand. For one-way mills with only an up-coiler the coil of strip delivered from the hot mill is wound off a pay-off reel, through a straightening machine to the rolling mill, and so to the up-coiler. Most frequently the mill has two coilers, and may also be equipped with a pay-off reel and delivery reel. For skin-pass and tempering mills there are also two sets of tension rolls which take up some of the tension necessary to obtain the high surface quality of the strip. This prevents the material from being damaged, and relieves the coilers at the same time. Tempering

Material	Usual strip widths in mm	Initial thicknesses in mm	Final thicknesses in mm	Maximum coil weight in t	Maximum strip tension in t
Steel	200-2000	1.5-4	0.1-1	30	45
Non-ferrous metals	40-1200	0.8-8	0.07-6	6	15
Light metals	250-2200	0.6-8	0.1-5	4	18
Foils	500-1600	0.02-0.7	0.003-0.05	3	1.5

mills only run in one direction. Finally, continuous strip mills are also used, consisting of three to five stands, usually four-high, with coilers and sometimes a pair of tension rolls between the last rolling stand and the up-coiler. In such tandem mills the strip is rolled in one direction, attaining its finished condition after the last stand.

Since the dimensional accuracy of the rolled material is very important for its subsequent treatment and has a considerable influence on the wear of the machines used, the stipulations regarding this factor are being steadily increased in severity. Not all disturbances can be effectively counteracted by suitable adjustments, so that in many cases automatic gauge control has to be provided, in order to attain the desired result. The simplest method of control is to measure the thickness after the rolling stand, e.g. by a contactless X-ray gauge. The values thus obtained are compared with a setting and the deviation utilized to obtain the appropriate correction, either by adjustment of the screwdown, the tension or the rolling speed. Good results can be obtained by this means. However, if the stipulations are still stricter, and the time-lag due to the distance of the measuring device from the rolling stand has to be taken into account, the thickness of the material has to be measured in the roll gap. Since, to a reasonable approximation, it may be assumed that the thickness of the material is equal to the roll gap, the latter can be measured and so provide the momentary value which has to be compared with the desired value. The roll gap is calculated with the aid of the screwdown in the unloaded state and two pressure gauges to determine the elongation, using the relationship

$$h = S_0 + F/M$$

- where h = roll gap or thickness of the strip
 S_0 = screwdown in the unloaded state
 F = rolling force
 M = modulus of the rolling stand

With the deviation in thickness so obtained, the control of the thickness can be effected through the tension in the strip and the screwdown. By this means the gauge can be maintained most accurately and it is possible to reach the limit imposed by the eccentricity of the rolls. Thus, for instance, 0.6 mm strip can be rolled to an accuracy of $\pm 7 \mu$.

Requirements to be Fulfilled by the Electrical Equipment

The requirements which the electric drives and their control gear have to fulfil are similar for all the different types of mills mentioned above. The description that follows may therefore be confined to the type of mill most common in Europe, namely the single-stand mill (see Fig. 1). The coil of material delivered from the hot-strip mill is fed into the stand from the down-coiler, or from a pay-off reel, passing through the straightener. The strip is introduced into the rolling stand at low speed, following which the mill and coilers are run up to full speed and finally braked electrically at the end of the pass. In reversing mills the strip is wound on to a second coiler during the second pass, the material being reduced to the required thickness by a number of passes in alternate directions.

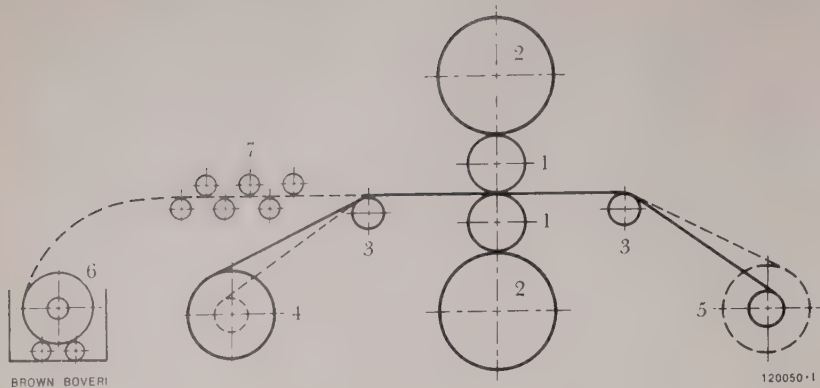


Fig. 1. — Basic layout of the single-stand cold-strip mill with down-coiler and up-coiler

- 1 = Work rolls
- 2 = Back-up rolls
- 3 = Deflector rolls
- 4 = Down-coiler
- 5 = Up-coiler
- 6 = Pay-off coil
- 7 = Straightener

For driving the rolling stand and the coilers it is standard practice almost everywhere to use d.c. motors, because they are the only machines which fulfil the strict requirements with regard to control.

The acceleration and braking times, especially when a high-grade system of gauge control is not provided, have to be kept as short as possible because the material rolled during these periods is not true-to-gauge.

The following conditions have generally to be fulfilled by the drive of the rolling mill, as it governs the working speed:

Running up according to a preset speed programme. Keeping the set motor speed constant during all disturbances, e.g. load or mains voltage fluctuation.

Short acceleration and braking times. The fly-wheel effect of the roll motor has therefore to be kept as small as possible by appropriate design of the machine.

For the coiler drive it is even more necessary to pay attention to the flywheel effect, as will be evident from the fact that it is the up-coiler which determines how short the acceleration time is. For this reason double-armature motors are often employed.

In order that the desired strip thickness may be maintained and the strip wound up uniformly, the tension produced by the up-coiler and down-coiler must be kept constant, not only during the coiling process at constant speed, but also during the acceleration and braking periods.

The product of the tension and the rolling speed, and the power required for acceleration and braking, determine the dimensions of the coiler drive. The coiler motor is regulated to an e.m.f. proportional to the rolling speed; its current comprises a component proportional to the tension, reduced or increased during the relevant period by the amount needed for acceleration or braking. The constant tension produces a torque at the coilers, which varies with the diameter of the coil. At constant strip speed the coiler speed is inversely proportional to the diameter of the coil. Since the tension and thus the coiler motor

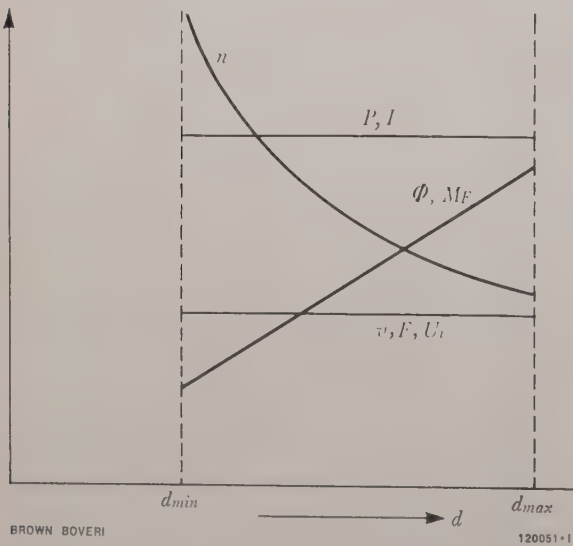


Fig. 2. — Curves showing the main electrical and mechanical quantities when rolling with coilers

- | | | |
|----------------|-------------------|------------------------|
| P = Power | Φ = Flux | M_F = Tension torque |
| I = Current | n = Motor speed | d = Coil diameter |
| U_i = E.M.F. | F = Tension | v = Strip speed |

voltage, as product of flux and speed, has to be constant the motor flux varies in proportion to the diameter of the coil. Fig. 2 shows the curves of the above mechanical quantities for constant working speed.

Feeding the Drive Machines

To feed the d.c. motors either Ward-Leonard sets or mercury-arc converters may be used. The latter are generally given preference on account of their high efficiency, and the ease with which they are installed and maintained, but for smaller powers the Ward-Leonard set may be quite sufficient. The supply may be from busbars or on the unit principle. In the latter case, where every drive has its own feed unit, the strict stipulations laid down for the drive can best be fulfilled, and consequently this system is most widely employed nowadays. When the supply is from busbars the motors are fed in parallel from a common generator or static converter set. This system is now seldom used and, since it does not offer any marked reduction in the outlay, will not be discussed further in the present article.

In the main circuit of the motors driving the rolling mill and the coilers it must be possible to reverse the current for a very short time because the torque produced by the drive machine in the periods of

acceleration, constant speed and braking may change its polarity. Moreover, in reversing mills the direction of rotation must also be reversible. Fig. 3 shows the most commonly used circuit arrangements. The power planes indicated provide information regarding the possible directions of the current, voltage and power.

When mercury-arc converters are employed, either the single or two-converter connection may be adopted. In the former case, as may be seen in Fig. 3b, it is impossible to reverse the current. Consequently reversal of the torque is effected by reversing the field. A single-converter connection with steady field reversal is employed in the "Contiflux" process [1]. It combines the advantages of contactless reversal by a steady change in the field with the minimum converter outlay. Since variation of the torque and speed present no difficulty, the Contiflux system can also be employed for reversing mills.

The cross connection (Fig. 3c) and the antiparallel connection (Fig. 3d) are two-converter arrangements permitting the current to flow in either direction. In this way the same behaviour is obtained as with the Ward-Leonard system, plus the advantage common to all static converter connections, i.e. the more rapid response resulting from the

Fig. 3. - Reversible motors fed from Ward-Leonard set or mercury-arc converters

- a: With Ward-Leonard set
 - b: Single-converter connection
 - c: Cross connection
 - d: Antiparallel connection
- M = D.C. motor
G = Ward-Leonard generator
MR = Mercury-arc converter

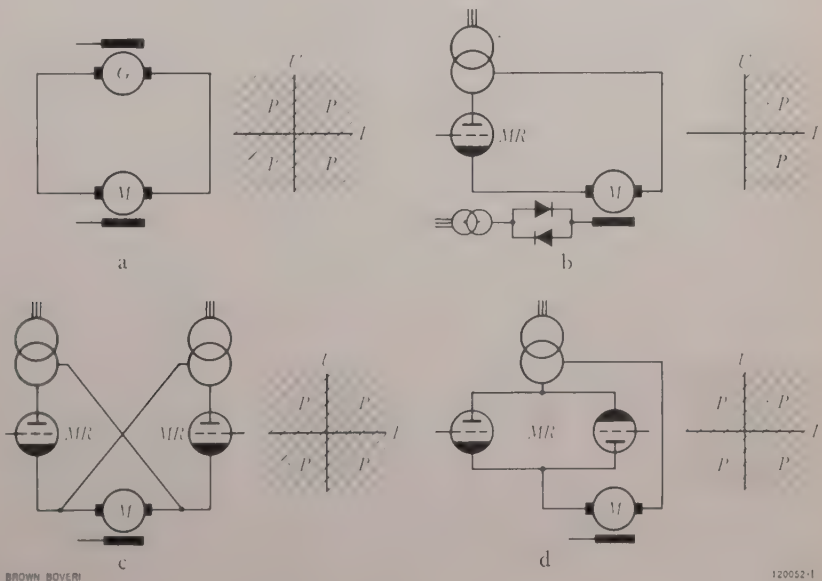


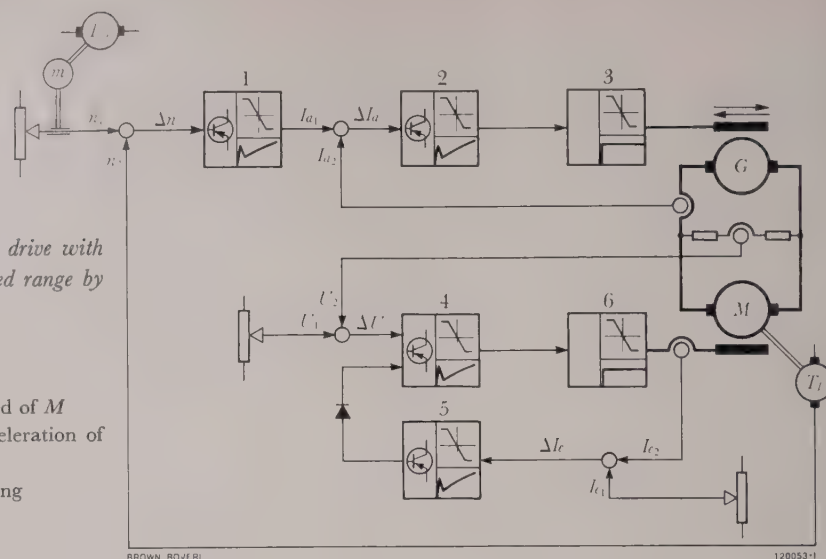
Fig. 4. — Variable-speed rolling mill drive with current limitation and extension of speed range by field-weakening

G = Ward-Leonard generator
 M = Rolling mill motor
 T_I = Tacho-generator measuring speed of M
 T_{IV} = Tacho-generator measuring acceleration of strip dv/dt
 m = Servomotor adjusting speed setting

1 = Speed controller
 2 = Armature current controller
 3 = Power stage for armature current control
 4 = Voltage controller
 5 = Excitation current controller
 6 = Power stage for field control
 n_1 = Desired speed

n_a = Actual speed
 I_{a1} = Desired armature current
 I_{a2} = Actual armature current
 U_1 = Desired armature voltage
 U_2 = Actual armature voltage

I_{e1} = Desired excitation current
 I_{e2} = Actual excitation current
 a = Basic component
 b = Simplified static characteristic
 c = Simplified transfer function



inertialess control of the mutators. The cross connection can be employed with single or multi-anode converters. The anti-parallel connection, however, utilizes the single-anode tanks described in earlier articles in this number (see page 623) and can manage with a simpler transformer. For low powers this arrangement can be operated three-phase, the somewhat higher harmonic content being usually admissible.

The two-converter connections may also be asymmetrical if only the torque has to be reversed for a short time, and if its value is small compared with the value in the working direction. This applies to the coiler drives and to the drives of non-reversing rolling mills. When the number of mutators is different for the two directions, an economical arrangement is obtained with a reduced number of tanks.

Asymmetrical two-converter connections may also be used to feed reversing rolling stands, because between two passes in alternate directions the polarity of the motor field can be reversed. By this means the work of rolling is always performed by the same

set of mutators. The brief torque reversal for braking is carried out by the smaller set, as with the one-way mill.

Control

Whether fed from static converters or Ward-Leonard sets, the control systems for the rolling mill and coiler drives are composed of building blocks of the Brown Boveri electronic system [2, 3, 4, 5].

Control of the Rolling Mill Drive

The drive of the rolling mill is equipped with speed control with current limitation, permitting it to run up to the desired speed with a preset rate of acceleration. The set speed, which determines the speed of the strip, must be maintained constant, regardless of external disturbances, such as fluctuation of the load. Otherwise the tension might vary in the strip, since the coiler and rolling stand are interlinked through the strip.

Fig. 4 shows the basic arrangement of the control system for a reversing mill with a Ward-Leonard set. By means of a motor-driven reference potentiometer the speed setting n_1 is applied to the control system and compared with the actual value n_2 provided by the tacho-generator T . Depending on the particular requirements, the run-up time can be selected between 5 and 30 s. A system of follow-up control allows the desired working speed to be pre-selected. When the strip is fed in, the drive can either be run at a very low speed or inched.

To prevent the drive from being overloaded, e.g. by trying to effect too great a reduction in one pass, the speed control loop is cascaded with a current control loop. For this inner loop a transistorized amplifier prescribes a reference value I_{a1} , obtained from the speed control loop. The system functions in such a way that, for instance, if the speed drops due to an increase in the load, the resultant speed difference Δn increases the desired value of the current I_{a1} , thus restoring the speed of the drive to its proper value. By means of the adjustable limitation of the reference value I_{a1} , the current is reliably limited without any overswing. Acting through another transistorized amplifier, the control loop drives the power stage which produces the excitation current for the field of the generator. With the aid of an appropriate means of super-excitation the magnetic inertia of the field is overcome and rapid response assured.

Depending on the particular economic and technical conditions, the correcting units may be based on magnetic amplifiers or equipped with mercury-vapour thyristors or controlled semiconductor rectifiers [6]. The Brown Boveri electronic system contains standardized and operationally tested ranges of such correcting units, adapted to the standardized signal voltages of the control units of the system.

To begin with, the speed is increased at full field by varying the motor voltage. On attaining its rated value, the armature voltage stays constant, while the motor speed continues increasing, because the field control acts on the excitation in the manner of field weakening, as may be seen in Fig. 4. The speed range

of the motor can thus be extended. The field control compels the field to retain its full value as long as the actual voltage value is smaller than the desired value, i.e. below the base speed. To obtain a quick stop in an emergency, optimum use is made of the braking power of the motor, the field being super-excited with the large voltage reserve. The field regulating circuit is equipped with a means of limiting the current, thus preventing the field coils from being overloaded when the motor speed is less than the base speed.

The effect of the above control system is that constant torque is available for the rolling mill drive up to the full motor voltage, and constant power at higher speeds.

In the event of a stoppage in the rolling mill, especially if the strip breaks, the drive has to be stopped quickly. Extremely short braking times are achieved with the above control system because it allows full advantage to be taken of the maximum braking power and torque of the motor with a minimum of delay. By suitably graduating the braking times of the down-coiler, the rolling mill and the up-coiler, the material can be prevented from looping during the braking process and being fed double into the roll gap, thereby causing damage to the rolls.

When the symmetrical or asymmetrical cross or anti-parallel connections are employed for feeding the rolling mill drives via static converters, the speed and current control loops are similar to those used with the Ward-Leonard set. Instead of the power stage 3 (Fig. 4) there is a grid control set per group of mutator tanks, which controls the converter concerned in accordance with the required speed and current programme. A logic circuit attends to the suppression of the "figure-eight" current, if necessary. The field control of the motor is effected in the same way as for the Ward-Leonard set. Thus the entire control system for a mutator-fed drive is the same as in Fig. 4.

The oscillogram in Fig. 5 shows the characteristic quantities—speed, armature voltage, armature current and excitation current—of a rolling mill drive.

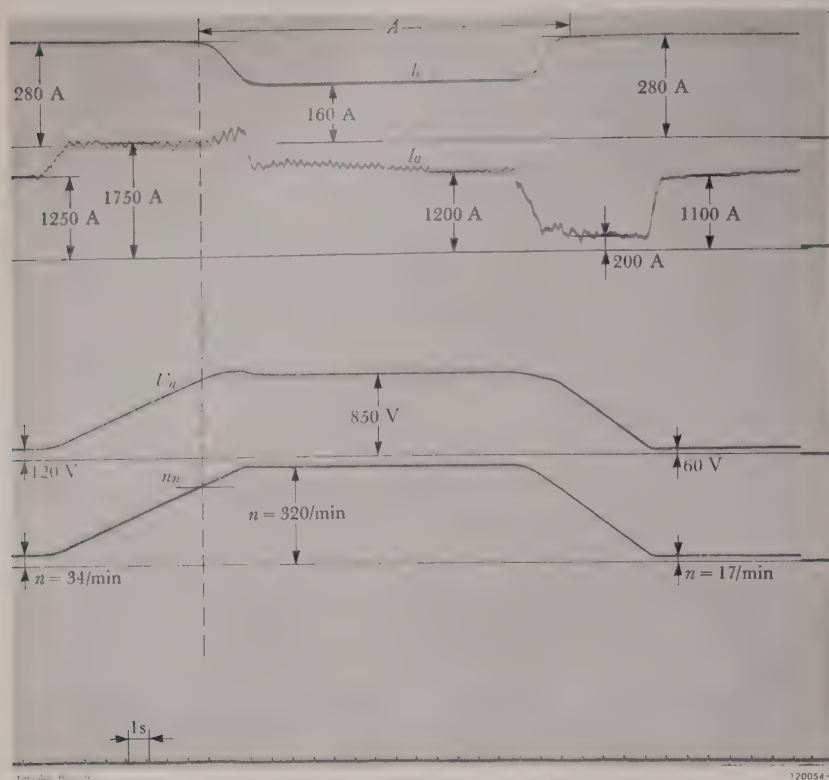


Fig. 5. — Oscillogram of the characteristic electric quantities of a rolling-mill drive

n = Motor speed (rev/min)
 U_a = Armature voltage
 I_a = Armature current
 I_e = Excitation current
 A = Field-weakening range

Clearly visible is the speed rise due to field weakening and the change in the armature current during the acceleration and braking periods.

In multi-stand trains, as with single-stand mills, the rolling mill drive is equipped fundamentally with speed control, but has an additional controlled and adjustable current influence. The individual stands can thus be set to a flat or drooping speed characteristic, depending on desired rigidity of the coupling between the separate stands.

The remarks that follow deal in rather more detail with the supply for rolling mill drives from mutators in the single-converter connection with field reversal, known as the Contiflux system [1]. Fig. 6 shows the basic arrangement of the main circuit and the control system. The economical single-converter connection only allows the current to flow in one direction, so that the torque and the speed have to be changed by reversing the polarity of the motor field. The characteristic physical behaviour of the Contiflux system is depicted in Fig. 7, showing the static characteristics for the armature current and flux of the motor.

As may be gathered from Fig. 6, the Contiflux system contains an overriding speed control loop

which, via the arithmetic unit I, simultaneously prescribes a definite value for the armature current and the flux. In this case the speed difference Δn between the desired and actual values is used as the input variable. The torque M , as product of the flux and armature current, is then determined by the variable Δn , as indicated in Fig. 7. The excitation current is steadily varied from positive to negative by the arithmetic unit, while the given armature current always remains positive, so that the characteristic is V-shaped. The motor torque can thus also be steadily varied in both directions. Since it is only dependent on the speed difference Δn , the torque required by the driven machine is produced at every positive or negative speed within the limits of the drive. The drive is properly controlled at all times and carries out the required speed programme without any abrupt change in the torque. Discontinuity in the torque would be transferred to the material and might lead to looping or the creation of additional tension in the strip.

The reference values determined for the flux and armature current by the arithmetic unit are applied to two subordinate control loops for motor field and

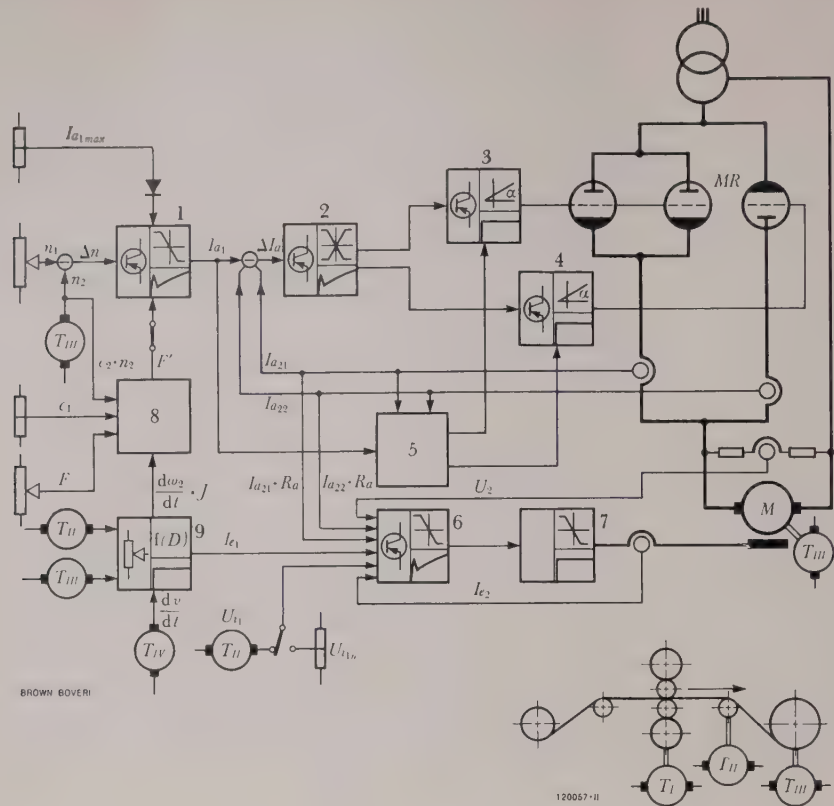


Fig. 8. – Up-coiler drive with controlled tension and speed

Fed in asymmetric anti-parallel connection with suppression of figure-eight current

- MR* = Mercury-arc rectifier

M = Motor driving coiler

T_I = Tacho-generator measuring speed of motor driving rolling mill

T_{II} = Tacho-generator measuring speed of strip

T_{III} = Tacho-generator measuring speed of coiler motor

T_{IV} = Tacho-generator measuring acceleration of strip dv/dt

1 = Speed controller

2 = Armature current controller

3, 4 = Grid control sets for controlling armature current

5 = Logic circuit for suppression of figure-eight current

6 = Controller for motor e.m.f. and excitation current

7 = Power stage for field control

8 = Arithmetic unit for corrected tension

9 = Arithmetic unit for acceleration component and desired value of excitation current as a function of the coil diameter

n_1, n_2 = Speed, desired and actual values

I_{a1} = Desired armature current
- I_{a1max} = Desired value of maximum admissible armature current

I_{a21}, I_{a22} = Actual armature current of first and second converter

F = Set tension

F' = Corrected tension

c_1 = Constant losses

$c_2 \cdot n_2$ = Losses varying with speed

$J \cdot d\omega/dt$ = Acceleration component

dv/dt = Acceleration of strip

U_{i1} = Setting of motor e.m.f. proportional to strip speed

U_{i1n} = Nominal value of desired motor e.m.f.

$I_{a21} \cdot R_a, I_{a22} \cdot R_a$ = Ohmic armature voltage drops which determine the actual value of the motor e.m.f.

I_{e1}, I_{e2} = Excitation current, desired and actual values
- | | | |
|----------|----------|---|
| <i>a</i> | <i>b</i> | <i>a</i> = Basic component |
| | <i>c</i> | <i>b</i> = Simplified static characteristic |

c = Simplified transfer function

retardation and diameter of the coil. In principle, it is possible to measure the tension direct with mechanical means and to apply it to the control system. The difficulty, particularly with small tensions, of obtaining accurate, reliable measurements by mechanical methods, and the fluctuation in the tension caused by the rolls being worn out-of-true, have resulted in the tension control being performed indirectly with the aid of electrical quantities. Apart from regulating to constant tension, which must also be maintained for a short time when the drive is at a standstill, speed control must also be provided for the introduction of the strip at the beginning of a coil, and for ending the rolling process after the last pass.

The output power of the coiler is given by the product of the working speed and the strip tension. Since the power is given by the product of the motor e.m.f. and the armature current, for tension control the strip speed is controlled in proportion to the motor e.m.f., and the tension in proportion to the armature current. These electrical quantities, however, yield the input to the motor. For the power output, therefore, the following corrections have to be taken into account and superposed on the desired value for the tension:

The losses in the machine which, to a first approximation, may be represented by a constant component and one proportional to the motor speed. For very strict requirements a quadripole can be employed as function generator for this correction of the desired tension value.

The power required for accelerating and retarding the rotating masses.

Fig. 8 shows the tension and speed control system for the coiler drive. The main circuit for the down and up-coiler may be an asymmetric two-converter connection. Since the pull of the coiler is always in the same direction, the second set of mutators only has to take over the current during retardation or for an emergency stop. They may be made correspondingly smaller for this short-time duty. In the connection in which the "figure-eight" current is suppressed, only one set of mutators is carrying current. A description of the anti-parallel connection with suppressed "figure-eight" current can be found in the article on page 650.

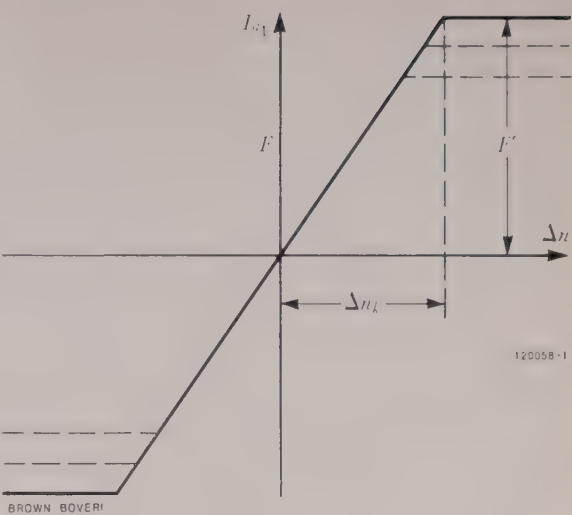


Fig. 9. - Strip tension and desired current as a function of the speed difference between actual and desired value

$$F' = F + c_1 + c_2 v + J \cdot d\omega/dt =$$

Corrected desired value of tension

$$F = \text{Set tension}$$
$$c_1 = \text{Constant losses}$$
$$c_2 v = \text{Losses varying with strip speed}$$
$$J \cdot d\omega/dt = \text{Acceleration component}$$
$$\Delta n = \text{Speed difference}$$
$$\Delta n > \Delta n_k = \text{Condition for constant tension}$$
$$I_{a1} = \text{Desired armature current}$$

The control system is basically arranged so that the current corresponding to the tension is controlled by the converters. The desired tension can be set with a potentiometer by the operator. The e.m.f. of the coiler motor is controlled in proportion to the strip speed by an appropriate adjustment of the motor field.

When feeding in the strip, the speed control first acts through the cascaded current control loop, exactly as for the Ward-Leonard set (Fig. 4). As soon as the tip of the strip has been attached to the coiler the desired speed value is raised slightly above the actual value. This causes the reference input I_{a1} to rise until the magnitude of the corrected tension F' has been attained, as introduced into the controller 1. I_{a1} is prevented from rising any further by the limitation circuit, as can be seen in Fig. 9. This circuit ensures that the change from speed to tension control takes place without jerking, so that the motor current can never exceed the level corresponding to the desired tension, on account of the limitation. During

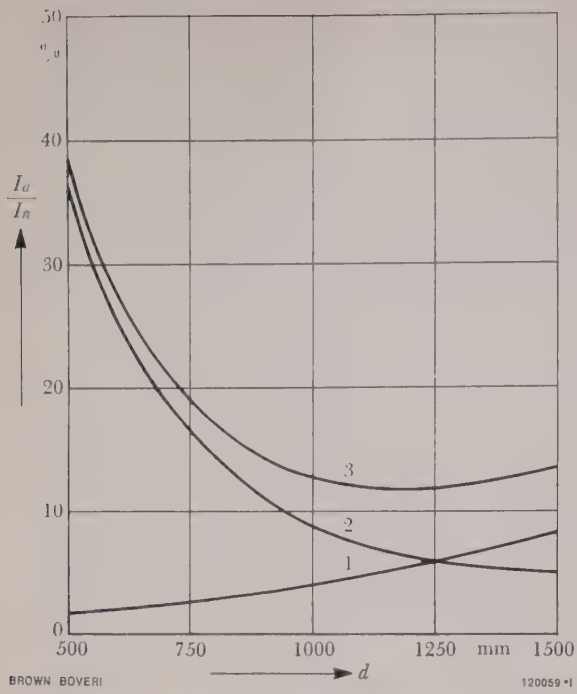
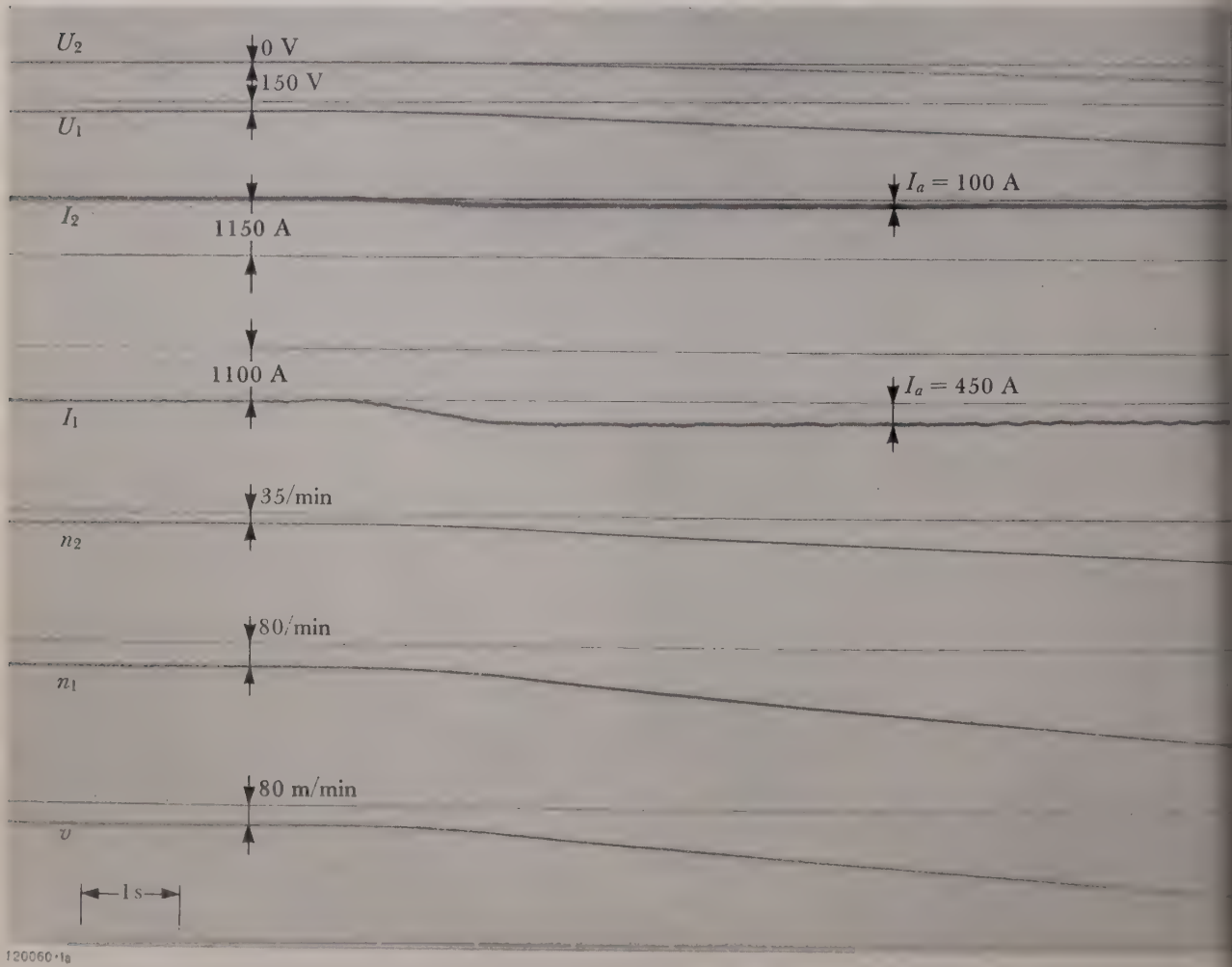


Fig. 10. – Relationship of acceleration current to rated current as a function of the coil diameter for constant run-up time to constant working speed

- I_a = Acceleration current
 I_n = Rated current
 d = Coil diameter
- 1: Coil alone
2: Motor
3: Coil and motor together

rolling the desired speed is always made higher than the actual value, thereby ensuring that the tension control is always in action.

In the event of the strip breaking, the drive is first accelerated to the desired speed, which is a little higher than the actual value. Then the speed control loop comes into action and prevents any further acceleration by reducing the reference input I_{a1} .



The speed limitation prevents the motor from running away.

The corrected value for the desired tension F' , which acts as reference value for the current control, is produced in the arithmetic unit 8. As shown in Fig. 9, this corrected tension value is determined by the following factors:

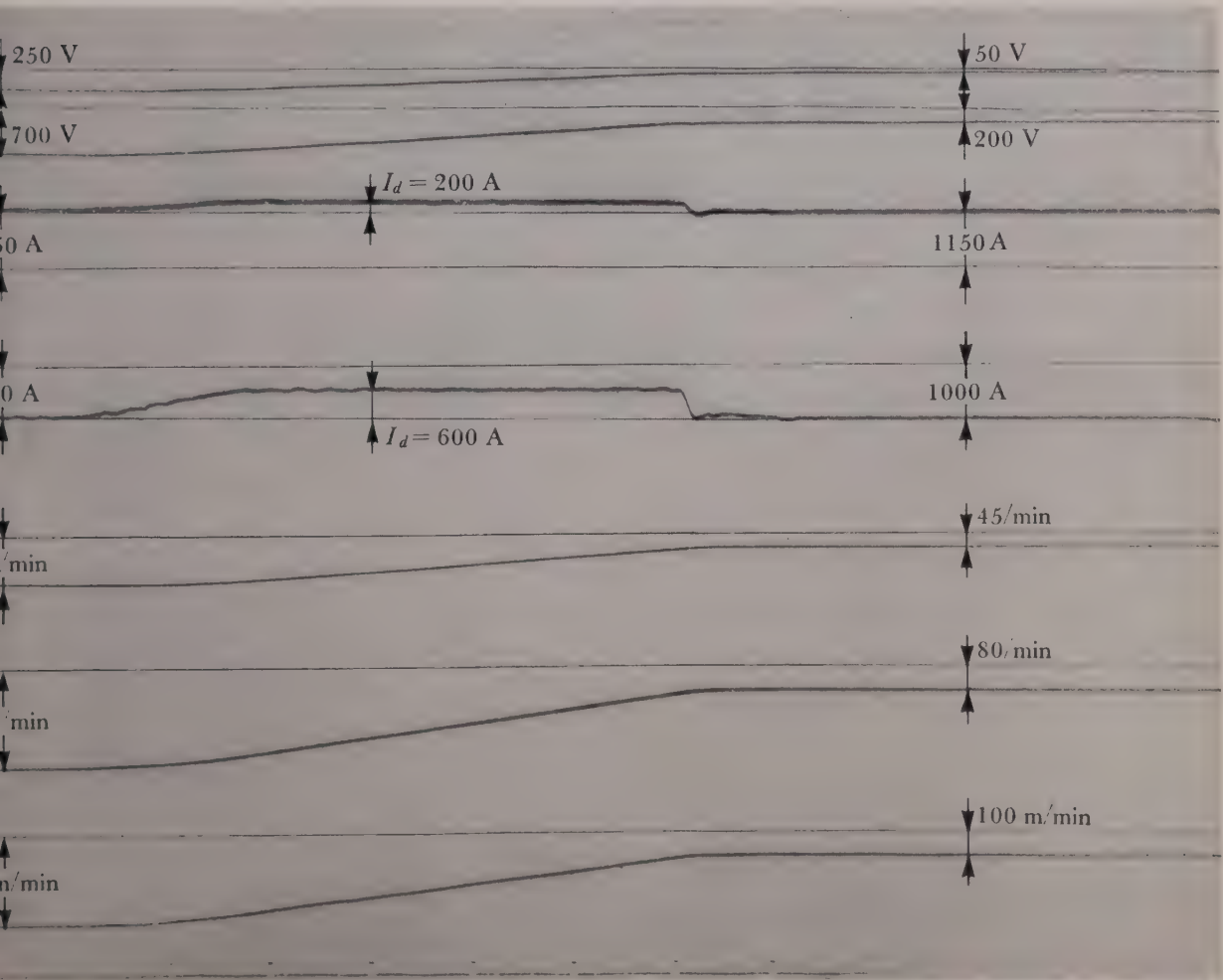
- F = Desired value for tension, set on a potentiometer
- c_1 = Constant losses
- $c_2 \cdot v$ = Losses proportional to the speed
- $J \cdot \frac{d\omega}{dt}$ = Acceleration influence of the coiler

The acceleration can be determined either by differentiating the voltage output of the coiler tachogenerator, or by a small tacho-generator on the servomotor of the potentiometer used for running up the rolling-mill motor (see Fig. 4). In the latter case it is assumed that the rolling stand and the coiler respond to the change in desired value instantaneously, an assumption which it is quite fair to make in view of the very small acceleration and the rapidity with which the control system responds.

In the arithmetic unit (Fig. 8) the moment of inertia J of the coil and the coiler is determined from the diameter, which itself is calculated from the

Fig. 11. – Oscillogram of the characteristic electrical quantities of the up-coiler and down-coiler

- v = Strip speed
- n_1 = Speed of up-coiler
- n_2 = Speed of down-coiler
- I_1, I_2 = Armature currents of up and down-coilers
- I_a = Acceleration current
- I_d = Retardation current
- U_1, U_2 = Armature voltages of up and down-coilers



speeds of the coiler and the strip, as given by the tachogenerators T_{II} and T_{III} . This value is multiplied by the value also fed into the arithmetic unit, giving the acceleration $d\omega/dt$, and yields the correction for the acceleration current. The curve showing the variation of the acceleration current in terms of the coil diameter d is shown in Fig. 10 [7].

The rolling stand and the coilers have to be run up as rapidly as possible so as to keep the loss of material low. The shorter the acceleration period, the greater the component of the acceleration current. With modern methods of control it is not unusual for the acceleration current to be six times the tension current, while maintaining the accuracy specified for the tension in practice. In this way extremely short run-up times are achieved, especially when the motors used have a very low flywheel effect.

As mentioned before, to produce the desired tension value, apart from controlling the tension current, the motor field has to be set so that an e.m.f. proportional to the strip speed is obtained. This is the task of the voltage control shown in Fig. 8. The voltage of the tachogenerator T_{II} running with the deflector roll is a measure of the desired value of the motor e.m.f. The voltage at the motor terminals, corrected by the ohmic drop in the armature $I_{a21} \cdot R_a$ or $I_{a22} \cdot R_a$, is utilized as actual value. By rapidly controlling the motor e.m.f. it is possible to correct for the field-weakening influence of the back-e.m.f. of the armature. If the tension in the strip has also to be maintained when the drive is at a standstill, the desired magnetic flux cannot be set with the aid of the voltage control; at standstill the motor e.m.f. is always zero regardless of the excitation current, so that the magnitude of the flux is indeterminate. Consequently a loop controlling the excitation, overriding the voltage control, comes into action, as can be seen in Fig. 8. Since, as shown earlier, the flux is merely a function of the diameter, the desired value for the excitation current can be obtained from the arithmetic unit concerned with the diameter. Before the e.m.f. becomes zero the arithmetic unit stores the values from the tachogenerators T_{II} and T_{III} and the diameter of the coil in the form of a potentiometer setting.

In the event of a stoppage or disturbance in the rolling operation, the drives of the rolling stand and the coilers have to be stopped as rapidly as possible. If the diameter of the coil is small, the motor flux and hence the possible braking torque is also correspondingly small. Therefore for emergency braking the field is increased as much as possible by stepping up the reference value of the voltage to the rated motor e.m.f. U_{i1n} and, at the same time, by raising the motor current to the maximum admissible value I_{a1max} .

With the control methods at present available and the elements of the Brown Boveri electronic system the control system can be designed for a very wide range of tension. Up to a ratio of 1:20 between minimum and maximum tension one coiler motor is employed. For higher tension ratios two motors are required, one of which is disconnected at lower tensions, thereby reducing the moment of inertia and friction losses, which would otherwise adversely affect the accuracy of the strip tension.

Naturally all coiler motors can also be fed from Ward-Leonard sets. The control system then conforms to the principle described above and the circuitry shown in Fig. 8 for a mutator-fed drive; the current control, as in Fig. 4, acts through a power stage on the field of the Ward-Leonard generator.

The oscillogram in Fig. 11 shows the conditions for the down-coiler and the up-coiler. The strip speed was recorded during an acceleration period, a period at constant speed and a braking period; also the speed, armature current and armature voltage of the two coilers.

The signal voltages for the control systems described for the drives of the rolling mill and the coilers are standardized, and the various available correcting elements adapted to the signal voltages. By means of the range of correcting elements developed by Brown Boveri the control systems can be matched to all power levels, permitting the fulfilment of all requirements imposed on the drives and control systems of all kinds of cold-strip mills.

(KME)

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BRIEF BUT INTERESTING

The Use of Low-Frequency Generators with Controlled Frequency and Voltage to Feed Roller-Table Motors

621.771.2-83:621.316.72

TO DRIVE the rollers of the transport systems in rolling mills, one of two methods is generally adopted nowadays:

- Either several rollers are driven by a common d.c. motor
- Or rollers are driven separately by squirrel-cage motors for industrial frequency supply, connected to the rollers through gearing and fed from a synchronous alternator, which in turn is driven by a d.c. motor.

In both cases the speed is controlled by the Ward-Leonard system.

A further possible method of driving the rollers is at present being executed by Brown Boveri. In this system each roller is coupled direct to a squirrel-cage motor; the motors are then connected to a Scherbius machine with a low output voltage and frequency, both variable. The field windings of the Scherbius machine are fed at industrial frequency via a frequency converter, which also separately controls the voltage and the frequency.

By feeding the squirrel-cage motors at low frequency it is possible to take advantage of the excellent current-torque characteristic. Whereas for geared motors operating at 50 c/s the short-circuit current is high and the starting torque low, by choosing a suitable low frequency it is possible to obtain an almost proportional relationship between the torque and the current. If the voltage is correctly matched, it becomes possible to operate with currents which are always of the order of magnitude of the rated current. The connection is suitable for reversal of the motors without using switches in the leads; it is also worth pointing out that braking energy is fed back into the mains. Hence a favourable power balance is achieved, allowing the cost of the converter to be rapidly amortized.

The controlled low-frequency squirrel-cage motor is thus a robust, reliable individual drive for roller tables. The low-frequency three-phase current can be generated in an easy manner by the converter set described.

(KME)

H. KOCH

New Continuous Merchant Mill for the Tata Iron and Steel Co. Ltd., Jamshedpur, India

621.771.272 (54)

HAVING regard to the increasing demand for rolled steel products on the Indian market, the Tata Iron and Steel Co. Ltd., Jamshedpur, decided to purchase a new merchant mill in 1957. The order for the mechanical part of the equipment was placed Messrs Schloemann of Dusseldorf, the electrical equipment being ordered from Brown Boveri. The complete installation comprises three separate rolling trains with the following stands and d.c. drive motors:

Roughing train with six stands

Stands 1 & 2, 450 mm dia., drive 400 kW, 0-350/1000 rev/min
Stands 3 & 4, 420 mm dia., drive 500 kW, 0-350/1000 rev/min
Stands 5 & 6, 420 mm dia., drive 700 kW, 0-350/1000 rev/min

Intermediate train with five stands

Stand 7 360 mm dia., drive 500 kW, 0-350/1000 rev/min
Stand 8 360 mm dia., drive 500 kW, 0-350/1000 rev/min
Edger 8a 580 mm dia., drive 400 kW, 0-350/1000 rev/min
Stand 9 360 mm dia., drive 500 kW, 0-350/1000 rev/min
Stand 10 360 mm dia., drive 500 kW, 0-350/1000 rev/min

Finishing train with four stands

Stand 15 360 mm dia., drive 700 kW, 0-350/1000 rev/min
Stand 16 360 mm dia., drive 700 kW, 0-350/1000 rev/min
Stand 17 360 mm dia., drive 400 kW, 0-350/1000 rev/min
Stand 18 360 mm dia., drive 400 kW, 0-350/1000 rev/min

The total load of the main drives (Fig. 2) amounts to 6200 kW.

In order to meet the stipulated rapid response of 0.25% s, all drives are connected on the unit principle and fed from grid-controlled pumpless mutators. The 400 and 500-kW motors each have one converter, the 700-kW motors two. Each converter is fed from a rectifier transformer; on account of the different motor ratings, two types of transformer were needed. For the 400 and 700-kW motors a transformer with a type rating of 845 kVA was provided, for the larger motors two units being provided. The converters for the 500-kW motors were fed through transformers with a type rating of 1050 kVA. The control system of this block consists of electronic elements mounted in drawout trays, which are thus readily interchangeable.

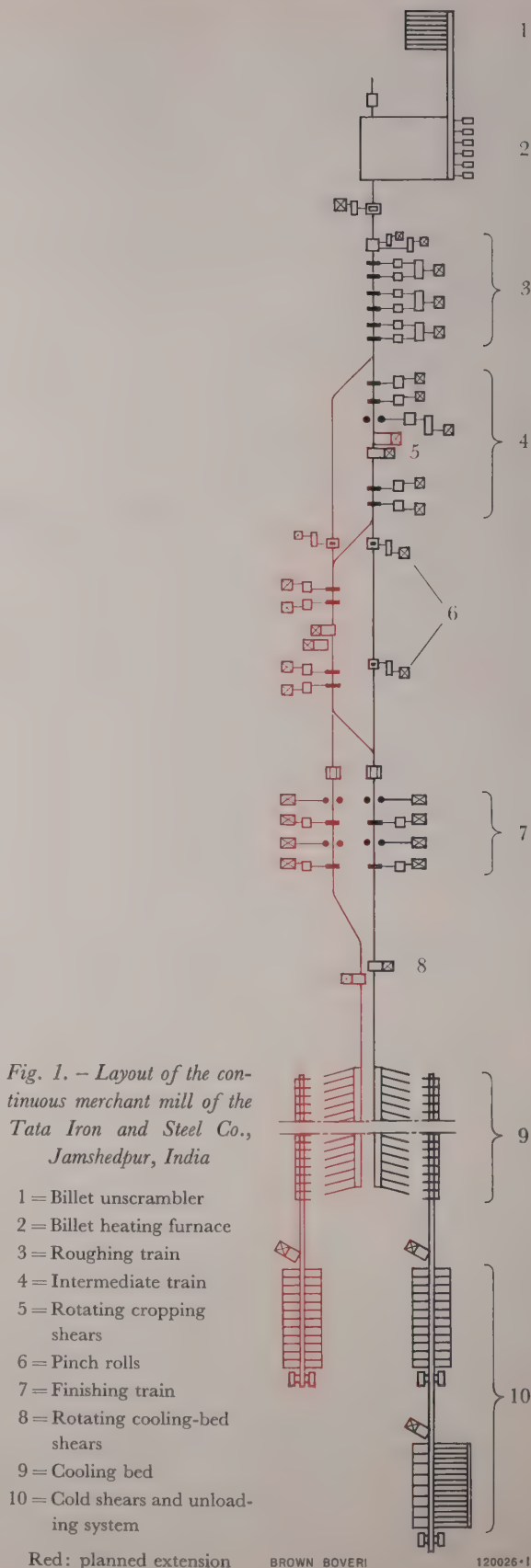




Fig. 2. — View of the motor house of the continuous merchant mill of the Tata Iron and Steel Co.

In the foreground are the four motors of the finishing train, the first two having a rating of 700 kW each, followed by two 400-kW motors. The basic speed of all motors is 350 rev/min. By field weakening the speed can be raised up to 1000 rev/min. The frequency changer supplying the motors driving the approach and run-in roller tables to the cooling bed can be seen in the background. This consists of a 500-kW, 1500-rev/min three-phase induction motor driving a d.c. motor rated 470 kW, 1500 rev/min; the second converter consisting of a d.c. motor rated 435 kW driving a synchronous alternator 117–450 kVA, with a power factor of appr. 0.55.

The speed of this set can be varied from 330 to 1500 rev/min.

For the auxiliary drives six transformers were provided, each rated 1500 kVA, stepping down from 13.2 kV to 440 V; only four of them are regularly in service, the other two acting as reserves. It is possible to switch over to these units without interrupting the supply. The drives for the billet unscrambler, the furnace, pendulum shears, rotating shears (d.c.), the pinch-rolls between the intermediate and finishing trains (d.c.), the rotating shears preceding the cooling bed (d.c.), the cooling bed itself, the cold shears, the water supply and the oil supply, represent a total load of 3110 kW. The Ward-Leonard system was adopted for the d.c. drives. The same applies to the frequency changer for the roller tables approaching and running into the cooling bed.

The supply for control of the main and auxiliary drives is obtained from a flywheel converter comprising a synchronous alternator driven by a three-phase induction motor. By this means brief interruptions of the mains supply are prevented from affecting the rolling mill by causing the majority of the contactors to drop out. In the event of the supply failing completely, the flywheel converter is able to maintain the control voltage for about 300 ms. This is sufficient to cover the interruption of faults in the high-voltage system which can be dealt with by rapid auto-reclosure of the breakers.

The stipulation of a high standard of dimensional accuracy for the finished product means that there must be no tension between the stands of the finishing train

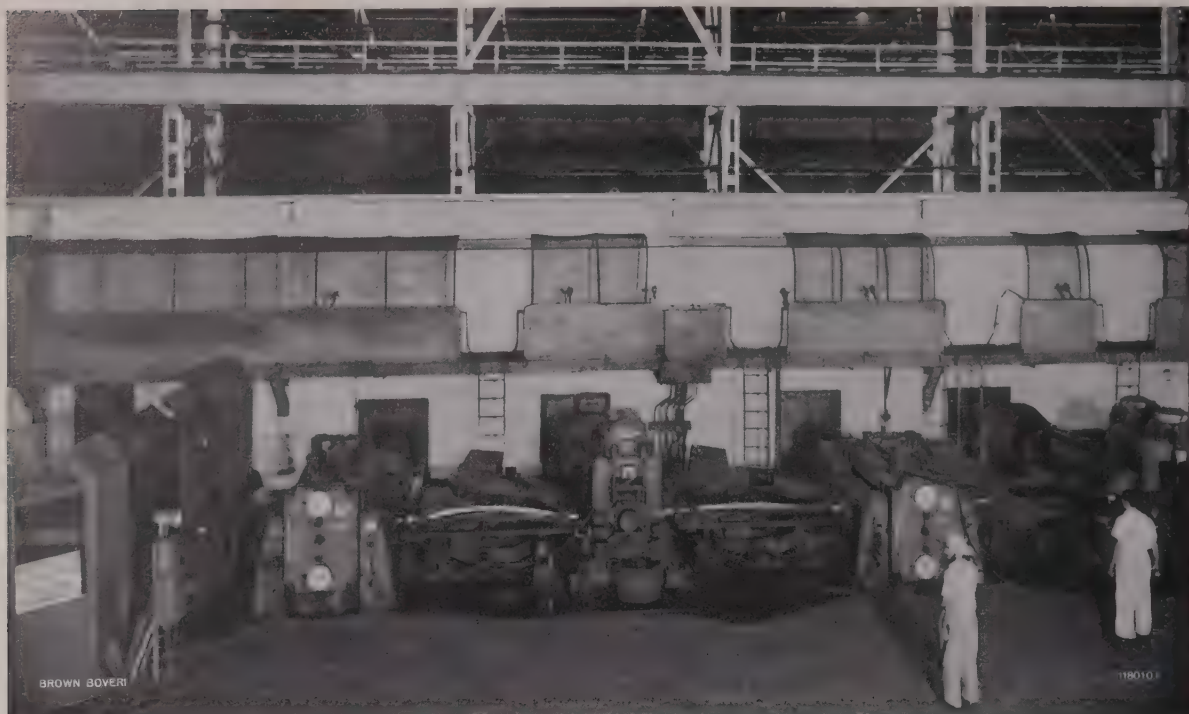


Fig. 3. — The stands 15 to 18 of the finishing train of the merchant mill at Jamshedpur

Clearly visible between the finishing stands are the looping devices; the horizontal loopers were in operation at the time this photograph was taken.

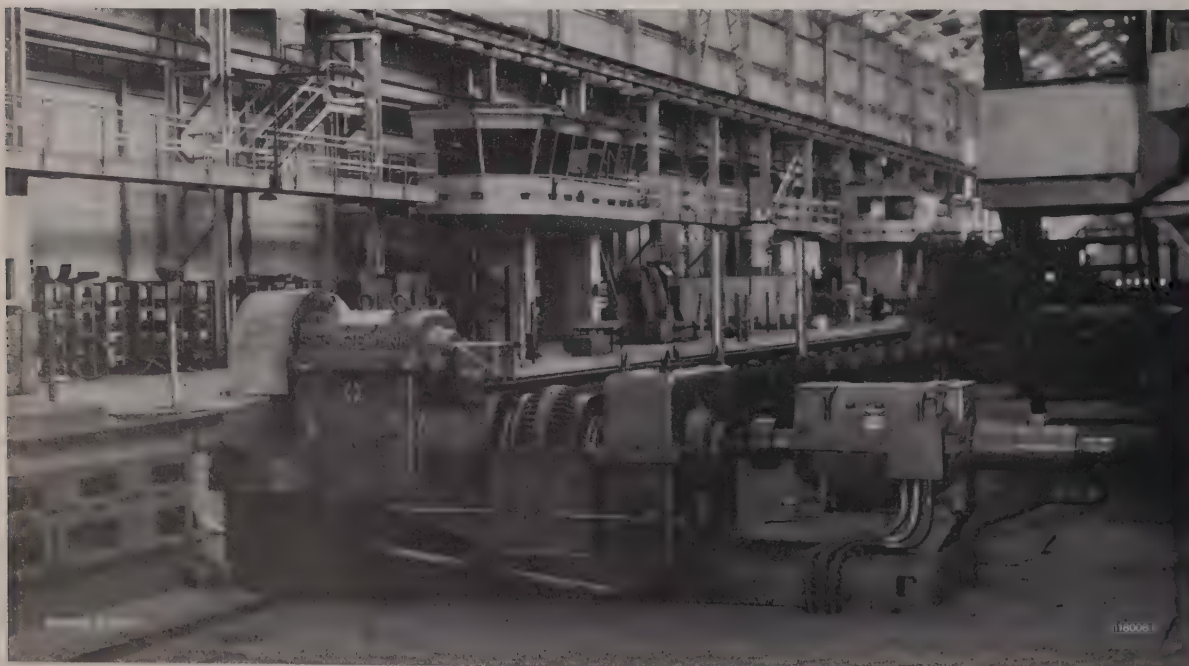


Fig. 4. — Cooling-bed shears of the merchant mill at Jamshedpur

Casing with the magnetic clutch and mill motor driving the shears, with its built-on tachogenerator and centrifugal switch. The mill motor conforms to the AISE size 610.



Fig. 5. — Cooling bed of the continuous merchant mill of the Tata Iron and Steel Co., Jamshedpur

The cooling bed consists of the approach and run-in roller table with main and secondary channel, the braking device, eccentric rake, shuffle bars and the run-out roller table. The cut lengths and position of the finished rods are clearly visible in the picture. This cooling bed is equipped with the automatic control system described in an earlier issue of the Brown Boveri Review (1960, Vol. 47, No. 3, p. 136-44).

and necessitated the incorporation of three vertical and three horizontal looping devices between these stands (Fig. 3). The vertical looping devices are used when rolling flats and angles; the horizontal ones when producing rounds.

The material emerging from the rolling mill is cut down with rotating shears (Fig. 4) to the length of the cooling bed, on which it is braked and cooled (Fig. 5). Two sets of cold shears following the cooling bed cut these pieces down to normal commercial lengths.

The mill was built for single-strand rolling to begin with. Provision has been made for two-strand rolling, however (Fig. 1, part shown in red). This will necessitate the provision of a second intermediate and finishing train and a further cooling bed. The number of stands and the drive power of the roughing train are already adequate to cope with two-strand rolling.

The cross-section of the billets prior to rolling are:

Billets	75 × 75 mm, 9.41 m long, weighing 411 kg
	100 × 100 mm, 9.41 m long, weighing 728 kg
Sheet-bars	127 × 100 mm, 9.41 m long, weighing 914 kg

The following finished products are turned out:

Rounds	12.7 to 63.5 mm dia.
Flats	23.8 to 127 × 6.35 to 50.8 mm
Squares	12.7 to 57.15 mm
Octagonals	19.5 to 38.1 mm
Angles	└ 25.4 to 76.2 mm
	└ 38.1 × 50.8 to 63.5 × 88.9 mm
Tees	38.1 to 63.5 mm
Channels	76.2 to 101.6 mm

The delivery speed of the mill amounts to 12 m/s at its maximum, when rolling rounds 12.7 mm dia. The capacity of the furnace is 75 t/h, the maximum output of the mill being 35 t/h of 12.7 mm rounds and 75 t/h of 20 mm rounds.

The installation of the electrical equipment for this mill was started in October 1959, for which Brown Boveri sent two supervisors to begin with, then a third in February 1960. When erection was at its peak, altogether 300 men were engaged on the electrical equipment alone. The erection was handled by Voltas Ltd., Brown Boveri's agents in India, employing Indian labour. In April and May 1960 Brown Boveri sent three commissioning engineers, whose task was to inspect the whole installation and adjust the controls. On August 3rd 1960, only ten months after erection was commenced, the rolling mill was placed in service personally by Mr J. R. D. Tata, Chairman of the Tata Iron and Steel Co. Ltd., and has been running very satisfactorily since.

(KME)

W. POHL

A New Sendzimir Mill in the Isbergues Steelworks of the Compagnie des Forges de Chatillon Commentry et Neuves Maisons (CCNM)

621.771.274 (44)

IN THE SPRING OF 1961 the CCNM took a new Sendzimir (cold-strip) mill into service in their Isbergues steelworks in France. The electrical equipment was supplied jointly by the Cie Electro-Mécanique, Paris and Brown Boveri. The mill consists of a rolling stand and two coilers, one on either side of the stand. During the first pass the strip is run off the rewinder, through a straightening machine into the rolling stand, and so to the up-coiler. For succeeding passes the whole system is reversed, so that the coilers operate alternately as up-coiler and down-coiler.

The material rolled is grain-orientated steel sheet containing silicon, as used for transformer laminations, also sheet-steel for coachwork and stainless steel sheet. The dimensions of the coils of strip range from 500 to 1065 mm wide, with diameters of 508 to 1830 mm. The weight of a coil may be anything from 9 to 20 tons.

Starting with a maximum initial thickness of 2 mm, the sheets are rolled down to a minimum of 0.3 mm in several passes.

The rolling mill is designed for a maximum rolling speed of 720 m/min, i.e. 12 m/s, a speed realized for the first time with this particular mill. At this maximum speed the tension in the strip amounts to 13.5 t; the maximum tension of 27 t is attained at a speed of 400 m/min. A feature deserving special mention is the emergency braking system which comes into action if the strip should tear. By means of a special electrical device, the mill and the coiler drive can be braked from the maximum speed of 720 m/min to standstill in 2.5 s.

The rolling mill and the two coilers are driven (Fig. 1) by five d.c. motors, each having a rated torque of 10 mt. The overall weight of these motors is roughly 42 t.



Fig. 1. — View of the motors driving the Sendzimir mill

The five d.c. motors are clearly visible: the motor for the rolling stand in the middle, with two motors for each coiler before and after the rolling stand.

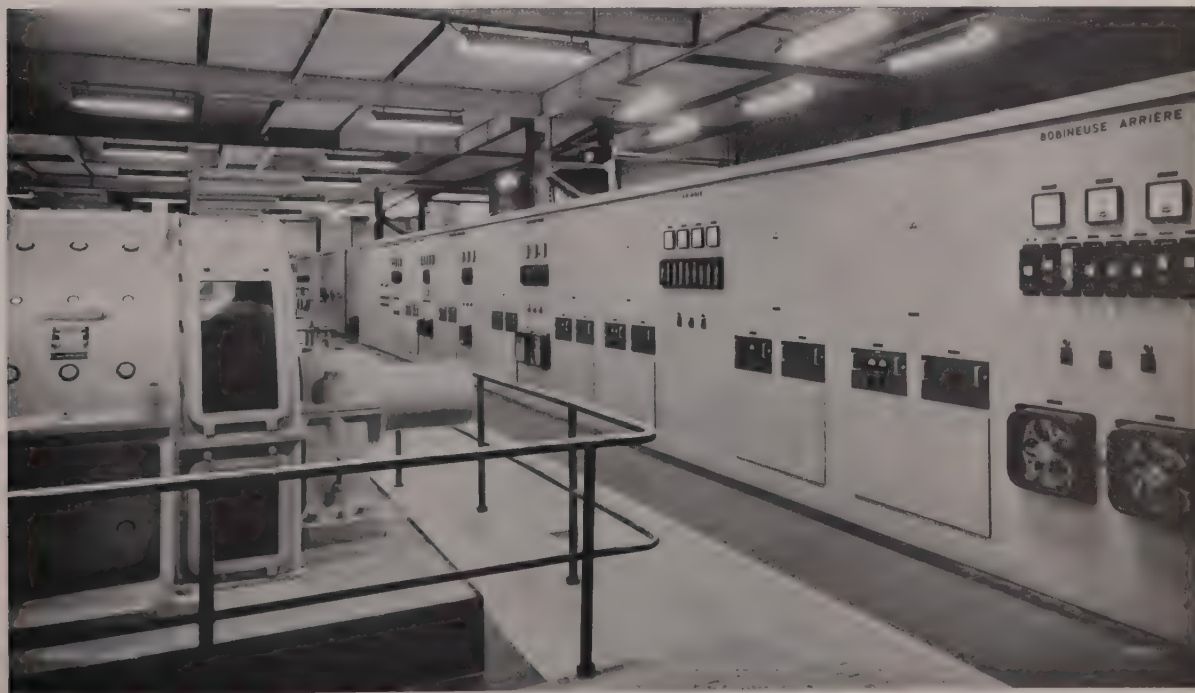


Fig. 2. — Switchboard containing the control gear for the main drives of the Sendzimir mill

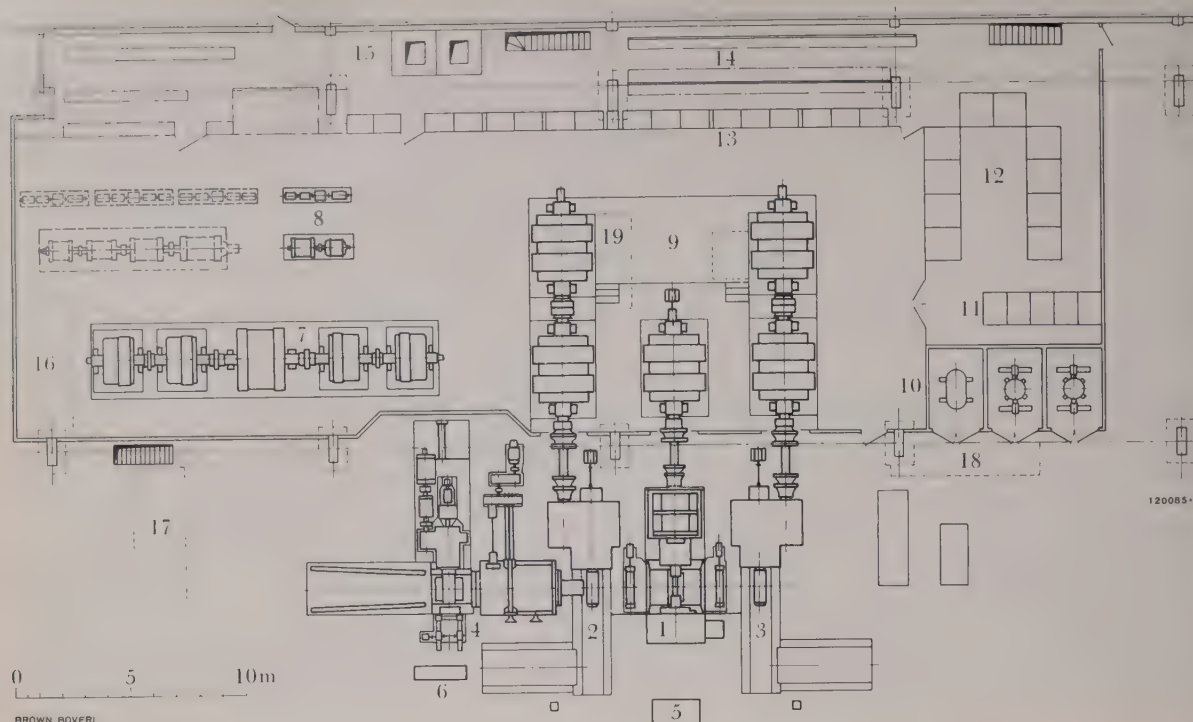


Fig. 3. - Layout plan of the Sendzimir mill, showing the rolling stand, drive motors, converter sets and switchgear

- | | |
|---|--|
| 1 = Sendzimir rolling stand | 12 = High-voltage switchgear 5.5 kV, 50 c/s |
| 2, 3 = Coilers | 13 = Switchboard with control gear, supervisory and signalling equipment |
| 4 = Rewinder | 14 = Contactor racks |
| 5 = Main control desk | 15 = Ventilation shafts |
| 6 = Control desk for the auxiliaries | 16 = Contactor rack in basement |
| 7 = Main converter set | 17 = Contactor rack for auxiliaries |
| 8 = Auxiliary converters | 18 = Contactor rack, hydraulic equipment |
| 9 = Motors driving the rolling stand | 19 = Control gear for the main d.c. motors of the rolling stand |
| 10 = Starting transformer for synchronous motor | |
| 11 = Low-voltage distribution board 380 V, 50 c/s | |

Their data:

Sendzimir mill drive	3500 hp, 0-250/600 rev/min
Coiler preceding the rolling mill	2250 hp, 0-150/340 rev/min
and	1250 hp, 0- 85/300 rev/min
Coiler following the rolling mill	2250 hp, 0-150/340 rev/min
and	1250 hp, 0- 85/300 rev/min

The two motors of each coiler are mechanically coupled, their armature circuits being in series; up to rolling speeds of 400 m/min both motors are in action and can produce a maximum torque of 27 t. On changing to higher speeds up to a maximum of 720 m/min, one motor is uncoupled and its armature short-circuited.

The d.c. motors are fed by a Ward-Leonard converter with a synchronous speed of 750 rev/min and a total weight of about 84 t. The set consists of:

Driving motor:

- 1 synchronous three-phase motor
- 7000 hp, 5 kV, 50 c/s,

Feeding the rolling mill drive:

- 2 d.c. generators 1470 kW,

Feeding the coiler before the rolling mill:

- 1 d.c. generator 2000 kW,

Feeding the coiler after the rolling mill:

- 1 d.c. generator 2000 kW.

In addition there are four auxiliary converter sets, as well as the drive for the rewinder. The installed capacity of these machines amounts to 2000 hp, and their total weight 17 t.

Finally, for various auxiliary drives in the rolling mill a total of 60 synchronous three-phase motors with a total capacity of about 2000 hp were required.

To accommodate the electronic control system, the open-loop control gear, the supervisory, signalling and measuring equipment, as well as the complete switchgear for the auxiliaries, the following installation was required:

1 switchboard 23 m long (Fig. 2)

1 contactor rack with 50 sections

1 main control desk with 6 subsidiary control desks and units

The current supply for the entire rolling mill is handled by a 5.5-kV switchgear installation housed in ten metalclad units. It contains the feeder terminal boxes, the starting gear for running up the synchronous motor of the main converter set at reduced voltage, the outgoing feeders to the two 1000 kVA transformers stepping down from 5500 to 380 V for the auxiliary supply mains, also the various instruments and kWh-meters. The overall layout is clearly depicted in Fig. 3.

(KME)

C. FOUCAULT

A Reversing Blooming Mill for Acciaierie e Laminatoi Monteforno S. A., Bodio, Switzerland

621.771.223 (494)

IN AUGUST 1961 a new, modern blooming mill was taken into service at the Monteforno steelworks in Bodio (Ticino). The mechanical equipment for the two-high reversing mill with pinion stand was supplied by Siemag, Dahlbruch, W. Germany. Brown Boveri provided all the electrical equipment, both for the main drive and for the auxiliaries.

The rolling stand is designed for cylinders ranging from 650 to 850 mm in diameter and 2000 mm long. It is used to produce billets and sheet-bars from preheated raw ingots weighing from 2.5 to 3 t.

In this rolling mill the following dimensions are of interest:

Weight of billets	0.6 to 3 t
Initial cross-sections	24 × 24 cm to 48 × 48 cm
Final cross-sections	
of billets	10 × 10 cm to 15 × 15 cm
of sheet-bars	8 × 18 cm to 13 × 30 cm
Number of passes	7 to 27 per ingot



Fig. 1. — Main motor of the reversing mill, rated 2600 kW at 60 rev/min, cut-out torque 120 mt



Fig. 2. — Mutator installation consisting of two sets of six single-anode tanks, feeding the main motor with field reversal

Output capacity	at present 30 t/h; after conversion to automatic control 40 t/h	Effective power	2600 kW
		Speed	$0 \pm 60 \pm 120$ rev/min
		Rated torque	42.2 mt
		Cut-out torque	120 mt

The work rolls are driven through a pinion stand by a d.c. motor, designed for the following data:

The d.c. motor is fed by two sets of six single-anode mutators (mercury-arc rectifiers), with anodes connected

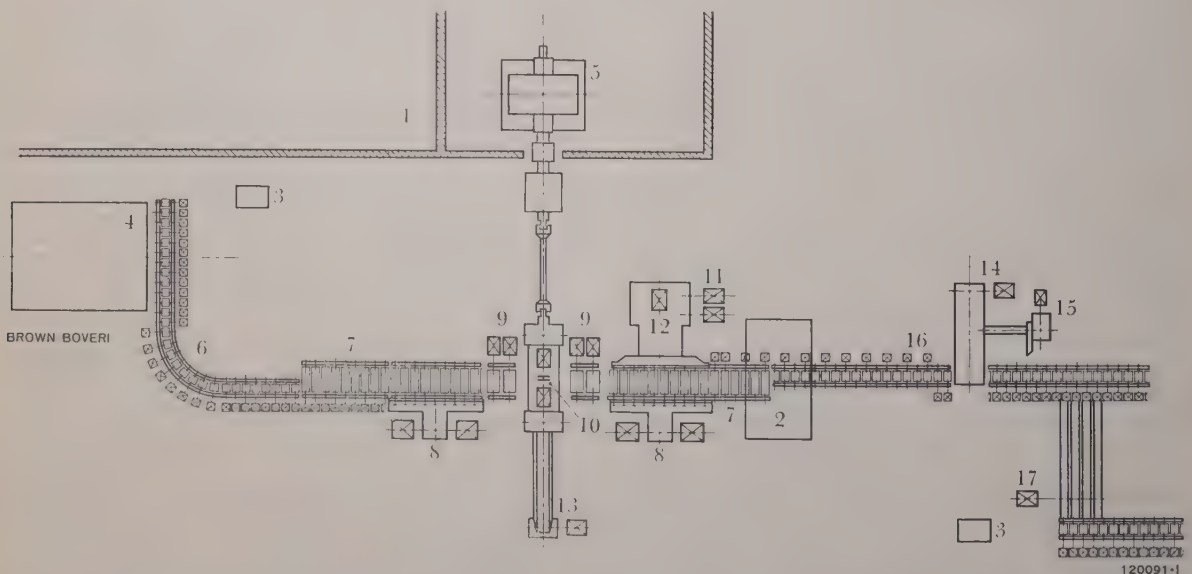


Fig. 3. — Layout of the reversing blooming mill in the Bodio steelworks of Acciaierie e Laminatoi Monteforno S.A.

- | | | |
|----------------------------------|------------------------------|-------------------------------|
| 1 = Distribution board | 7 = Extension roller tables | 13 = Roll-changing gear |
| 2 = Control pulpit | 8 = Working roller tables | 14 = Billet shears |
| 3 = Control desk for auxiliaries | 9 = Feed rolls | 15 = Stop |
| 4 = Soaking pit | 10 = Screwdown gear | 16 = Roller table from shears |
| 5 = Reversing main motor | 11 = Manipulator side-guards | 17 = Transfer skid |
| 6 = Approach roller table | 12 = Tilting device | |

in pairs in parallel. They are connected to the h.v. supply via a transformer with interphase transformer. The design of the mutator installation is such that an ingot can be finished at full torque with only one set of six single-anode mutators.

In the armature circuit the mutators are connected for half-wave rectification; the direction of rotation of the main motor is reversed by changing the polarity of its field current. By means of a specially designed exciter the excitation current can be increased to five times its normal value (super-excitation). The use of this rapid exciter, and the provision of laminated main and interpoles and yoke for the main motor allows the field to be reversed very rapidly, and very short reversing times attained.

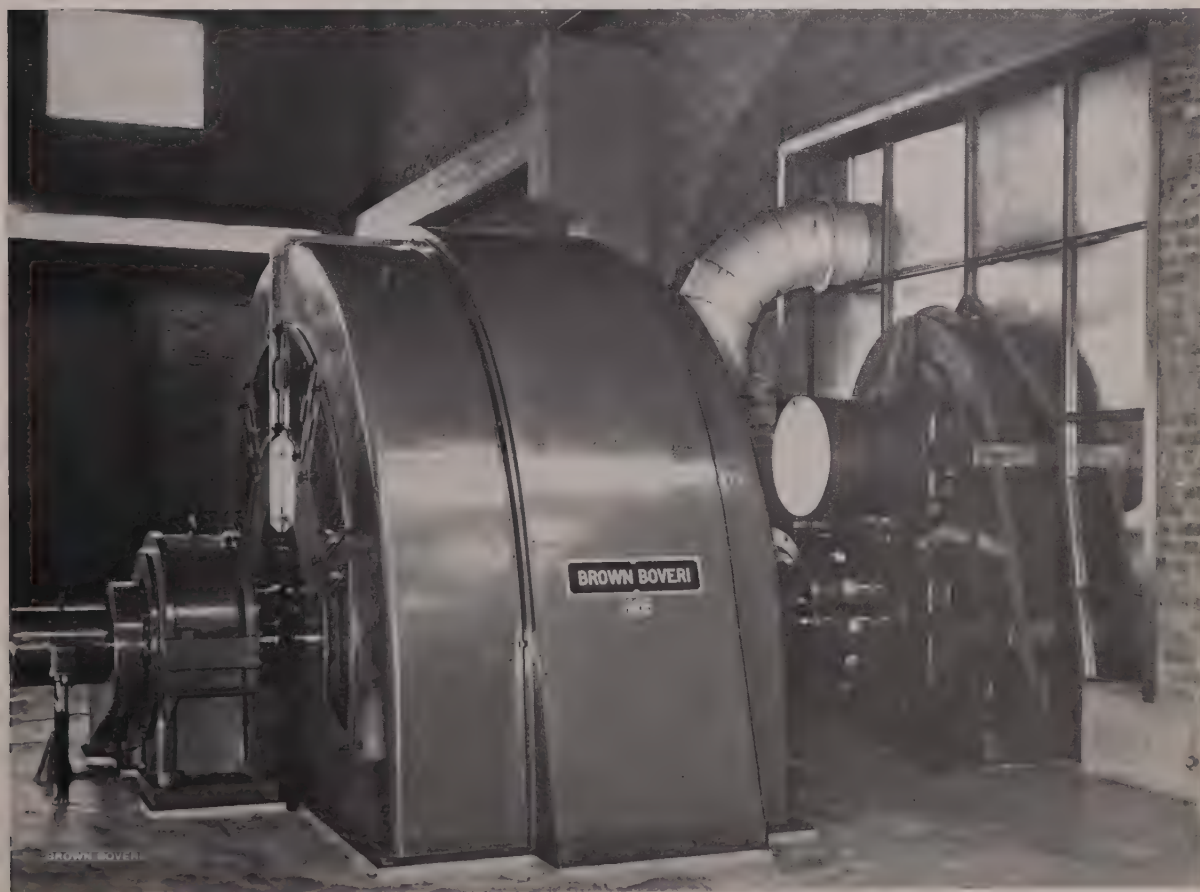
An electronic control system ensures that the drive obeys the control commands exactly, but at the same time that inadmissibly high stresses are not imposed on the motor or mutators. This control system comprises the following principal circuits: A current control

circuit ensures that the maximum admissible motor current is not exceeded. A voltage control circuit monitors the armature voltage and keeps it at its rated value while operating with field-weakening. These circuits are overridden by a speed control circuit. Finally a means of limiting the acceleration prevents unduly high reactive load peaks from occurring. All elements of the control system supplied for this reversing mill are designed for automation at a later date. At present manual control is provided.

The screwdown of the upper roll of the two-high stand is effected by a pair of mill motors, each rated 60 kW at 600 rev/min. A Ward-Leonard converter controlled by magnetic amplifiers feeds these two motors. For the remaining auxiliaries such as the roller tables, pushers, tilting device, as well as the billet shears and hot shears, together with various a.c. auxiliaries, machines were installed having a total rating of over 1000 kW.

(KME)

G. CREMONCINI



Svenska Kullagerfabrik, Hällefors, Sweden. Rolling-mill motor rated 2900 kW, 60, 120 rev/min, cut-out torque 150 mt

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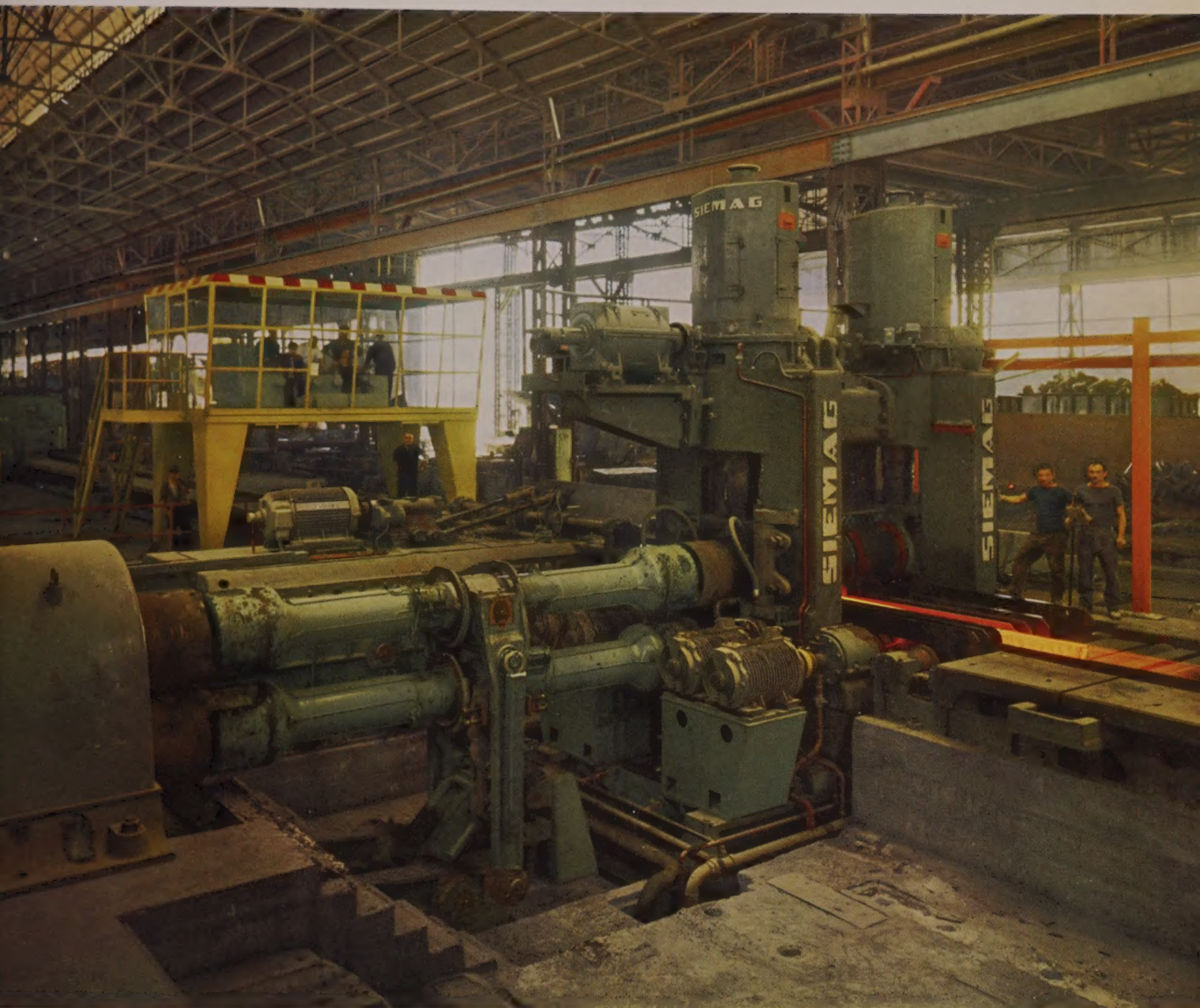
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View of the blooming mill of Acciaierie e Laminatoi Monteforno S.A., Bodio, Switzerland

In the foreground is a two-high stand with spindles and pinion stand. One of the two 60-kW mill motors driving the screwdowndown gear is mounted on a bracket attached to the stand.



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